Quantifying Climate Change Effects of Bioenergy and BECCS: Critical Considerations and Guidance on Methodology

Citation for the original published paper (version of record):
Cowie, A., Koponen, K., Benoist, A. et al (2025). Quantifying Climate Change Effects of Bioenergy and BECCS: Critical Considerations and Guidance
on Methodology. GCB Bioenergy, 17(10). http://dx.doi.org/10.1111/gcbb.70070

GCB Bioenergy

WILEY

Global Change Biology Bioenergy
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY

REVIEW OPEN ACCESS

Quantifying Climate Change Effects of Bioenergy and BECCS: Critical Considerations and Guidance on Methodology

Annette Cowie[1,2] | Kati Koponen[3] | Anthony Benoist[4,5,6] | Göran Berndes[7] | Miguel Brandão[8,9,10] | Leif Gustavsson[11] | Patrick Lamers[12] | Eric Marland[13] | Sebastian Rüter[14] | Sampo Soimakallio[15] | David Styles[16]

[1]University of New England Armidale, Armidale, Australia | [2]NSW Department of Primary Industries and Regional Development, Armidale, Australia | [3]VTT Technical Research Centre of Finland, Espoo, Finland | [4]CIRAD, UPR BioWooEB, Saint-Denis, La Réunion, France | [5]BioWooEB, CIRAD, Université de Montpellier, Montpellier, France | [6]Elsa, Research Group for Environmental Lifecycle and Sustainability Assessment, Montpellier, France | [7]Chalmers University of Technology, Gothenburg, Sweden | [8]Department of Sustainable Development, Environmental Science and Engineering (SEED), KTH Royal Institute of Technology, Stockholm, Sweden | [9]Faculty of Natural Sciences and Technology, Riga Technical University, Riga, Latvia | [10]Sustainable Energy & Environmental Systems, Energy Analysis & Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA | [11]LG-Energikonsult Lund Sweden, Lund, Sweden | [12]National Renewable Energy Laboratory, Golden, USA | [13]Appalachian State University, Boone, USA | [14]Thünen Institute of Wood Research, Hamburg, Germany | [15]Finnish Environment Institute SYKE, Helsinki, Finland | [16]School of Biological & Chemical Sciences and Ryan Institute, University of Galway, Ireland

Correspondence: Annette Cowie (annette.cowie@dpird.nsw.gov.au)

Received: 18 January 2025 | **Revised:** 30 June 2025 | **Accepted:** 22 July 2025

Funding: K.K. and S.S. acknowledge financial support for the green transition by the European Union (NextGenerationEU/151 P5C1I2, project REPower-CEST). G.B. acknowledges financial support from The Swedish Energy Agency (Navigating synergies and tradeoffs towards future forest-based solutions), The Swedish Agency for Economic and Regional Growth (Concrete action in the cement industry and the cement and concrete supply chain) and the European Union's Horizon Europe research and innovation program under the UPTAKE project (grant no. 101081521).

Keywords: BECCS | BiCRS | bioCCS | bioenergy | biogenic carbon | biomass | carbon footprint | CDR | life cycle assessment | system boundary

ABSTRACT

Bioenergy is a critical element in many national and international climate change mitigation efforts, including as a carbon dioxide removal strategy combined with the capture and durable geological storage of flue gas emissions (BECCS). However, divergent results on the effectiveness of bioenergy as a climate change mitigation measure are reported in the scientific literature. Climate impacts of bioenergy depend on case-specific factors, primarily biophysical features of the biomass production system, and the design and efficiency of conversion and capture processes. Estimates of climate impacts are also strongly affected by methodological choices and assumptions, and much of the divergence between studies derives from differences in the assumed alternate use of the land or feedstock, the alternate energy source and the system boundaries applied. We present a methodology to support robust estimates of the climate change effects of bioenergy systems, updating the standard methodology developed by the International Energy Agency's Technology Collaboration Program on Bioenergy. We provide guidance on the key choices including the reference land use and energy system that bioenergy is assumed to displace, spatial and temporal system boundaries, co-product handling, climate forcers considered, metrics applied and time horizon of impact assessment. Researchers should consider the whole bioenergy system including all life cycle stages, and choose system boundaries, reference systems and treatment of co-products that are consistent with the intended application of the results. The assessment should be normalised to a functional unit that can be compared with other systems delivering an equivalent quantity of the same function. All significant climate forcers should be included, and climate effects should be quantified using appropriate impact assessment methods that distinguish the impact of time. Consistency in methodology and interpretation will facilitate comparison between studies of different bioenergy systems.

1 | Introduction

Bioenergy, both without and with carbon capture and storage (BECCS), is anticipated to play a key role in meeting the temperature goal of the Paris Agreement (IPCC 2018). However, the climate benefits of bioenergy systems have increasingly been questioned. With respect to forest-based bioenergy, some studies show large 'carbon debt' or foregone sequestration that may take decades to repay before delivering climate benefits (e.g., Hudiburg et al. 2011; Schulze et al. 2012; Kallio et al. 2013; Pingoud et al. 2016; Soimakallio et al. 2016; Walker et al. 2010), whereas others show that benefits can also be immediate (e.g., Abt et al. 2012; Cintas et al. 2016; Favero et al. 2020, 2023; Gustavsson et al. 2015; Lamers and Junginger 2013). In the case of annual bioenergy crops, some studies raise concerns over direct and indirect land use change (iLUC), high N_2O emissions and loss of soil organic matter (e.g., Fargione et al. 2008; Gibbs et al. 2008; Searchinger et al. 2008; Yang and Suh 2015) and payback times of many decades (Yang and Suh 2015), whereas others demonstrate substantial net climate benefits (Sydney et al. 2019), payback of less than a year (Elshout et al. 2019), and that displacement effects can even reduce the need for annual crop production elsewhere (Englund et al. 2023).

These widely divergent results present a confusing picture for policy-makers and energy consumers. While some differences between studies relate to fundamental differences between bioenergy systems, others arise from analytical choices made by the analyst as well as through interpretation of the results. Bioenergy systems differ with respect to biomass source (e.g., forest or crop residues, purpose-grown crops, processing wastes), bioenergy products (solid, liquid or gaseous fuels, with different properties and applications), conversion technologies (ranging from open fire combustion to advanced technologies for liquid biofuels) and facility scale. These factors all contribute to divergent results between studies of different bioenergy systems (e.g., Cherubini et al. 2009). Variations arising due to differences in the analytical methods, such as the system boundary, handling of co-products, spatial scale, land use scenarios and treatment of time, can have a large impact on the results (e.g., Benoist et al. 2012; Brandão et al. 2019). In addition, interpretation of the results is sometimes not consistent with the methods applied (Agostini et al. 2019). It is critical that analysts are aware of the impacts of their choices, that they apply transparent methods suited to the intended application and that the interpretation is consistent with the methods used. Application of consistent approaches will support valid comparisons between studies. The need for guidance on the selection of suitable methods, to support enhanced consistency, has been widely recognised (e.g., Agostini et al. 2019; Muench and Guenther 2013; Roos and Ahlgren 2018).

This paper presents the standard methodology for quantifying climate change effects of bioenergy developed by the International Energy Agency's Technology Collaboration Program on Bioenergy. It expands and updates the earlier 'standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems' (Schlamadinger et al. 1997), incorporating recommendations from recent publications by the IEA Bioenergy research network, plus other relevant literature. Our aim is to support researchers, policy advisors and decision makers in government and non-government sectors to evaluate climate effects of bioenergy and BECCS using consistent and valid approaches, methods and assumptions that are suited to the purpose of the assessment and to appropriately interpret and apply the results. The methodology is intended to provide a comprehensive understanding of climate effects, when the goal is to inform policy development. We also provide guidance on methods that are applicable for routine application, such as in policy implementation. The methodology presented is equivalent to a framework standard, describing the scope, conceptual approach and elements to include. It could form the basis for development of a more detailed technical specification.

Forest-based bioenergy is a particular focus of the paper because it presents several complexities for analysis of climate change effects. Quantifying climate effects of bioenergy based on biomass from agricultural systems is also discussed, and specific guidance for assessment of BECCS systems is also included. The majority of the guidance is applicable to all bioenergy systems.

We first discuss basic concepts such as the carbon cycle, life cycle perspective and the timing of emissions and removals in forest bioenergy systems. Then we examine key issues in quantifying the climate effects of bioenergy, including the modelling approach, selection of spatial and temporal boundaries and the handling of co-products. The role of non-GHG climate forcers and the choice of methods to measure climate impacts are briefly considered. Finally, we provide recommendations to guide climate impact assessment of bioenergy.

2 | Key Concepts

2.1 | The Carbon Cycle and 'Carbon Neutrality'

Fossil fuel use causes emissions of carbon (as CO_2 and CH_4) that has been securely stored in geological formations for millions of years and that is not replenished over human-relevant timescales. It can therefore be regarded as an irreversible flow of carbon from geological reservoirs to the atmosphere. Any fossil fuel emissions arising from the production, processing and transport of biomass and bioenergy products need to be included when calculating the climate effect of bioenergy.

In contrast to fossil fuels, bioenergy systems influence the short-term carbon cycle (driven by photosynthesis, respiration, decay and combustion) and can affect the storage of carbon in other bio-based products. Bioenergy is carbon neutral in regard to actual biogenic carbon flows if producing and using the biomass for bioenergy results in zero or negligible net emissions of biogenic CO_2 to the atmosphere when the complete life cycle of plant growth (and regrowth), harvesting and consumption of biomass is considered (Albers et al. 2019; Strengers et al. 2024). In the case of forest-based bioenergy, if the average forest carbon stock (in live biomass, litter and soil) remains stable as the cycle of growth and harvest is repeated over time, there is no net biogenic CO_2 emission. However, rather than being completely carbon neutral, bioenergy systems usually change the carbon stock in the vegetation, soil or bio-based products pools compared to a situation without this biomass supply for bioenergy, for example, by changing the mean residence time of sequestered carbon or the land area used for sequestration; this decrease or increase represents an emission or removal of biogenic carbon, respectively, that must be considered.

While inherently transient at small scale (a single tree, a newspaper, a house), the accumulation of biospheric carbon pools creates a long-term reservoir of carbon. Bioenergy systems have the potential to decrease or increase the C stocks of these pools; for example, by changing the mean residence time of sequestered carbon or the land area used for sequestration.

Bioenergy systems should not be assumed to be carbon neutral; rather, the life cycle emissions and removals should be considered, including changes in biogenic carbon pools compared to the reference system (i.e., 'no bioenergy' case), over explicit time horizons to show how bioenergy affects the climate in the short and long terms. This is particularly important given the urgent need to balance carbon fluxes to and from the atmosphere in order to stabilise the climate (IPCC 2021).

2.2 | Life Cycle Perspective

Life cycle assessment (LCA) is a framework for assessing the environmental impacts of product systems and decisions (ISO 2006a, 2006b). It is commonly applied in studies that quantify climate impacts of bioenergy. Unlike national GHG emission reporting and accounting (Box 1), which focuses on actual annual emissions and removals at the country level, LCA considers the entire life cycle of a product or service. The steps in LCA are (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment and (4) interpretation of the results. LCA can be applied to product systems of different scales and can be used to aid micro- and macro-level decisions (EC-JRC-IES 2010). The assessment should include GHG emissions and removals related to biomass procurement, such as planting and harvest; manufacture of inputs such as fertiliser; transport, storage and conversion of biomass and product storage, distribution and use (Ter-Mikaelian et al. 2015). Inputs across the supply chain (e.g., fossil fuels, fertilisers, processing chemicals) vary between bioenergy systems, depending on the biomass source, conversion process (e.g., combustion, gasification, anaerobic digestion), carrier (solid, liquid, gas) and end use (e.g., transport, heat, electricity). For BECCS systems, the assessment should include fuel use for CO_2 capture, compression, transportation and injection, and possible CO_2 leaks from pipelines and injection sites (Erlandsson and Tannoury 2020; Gholami et al. 2021; Briones-Hidrovo et al. 2022). Emissions due to construction and demolition of facilities (e.g., establishment of forest roads, construction of processing plant and power distribution infrastructure) are omitted in many LCA studies but should not be automatically excluded without justification. Where included for the bioenergy system, equivalent construction and demolition emissions should also be considered for the reference energy system (see Section 3.4). Net biogenic carbon emissions from the land (i.e., changes in carbon stocks in vegetation and soil relative to a reference scenario without bioenergy, see Section 3.4) must be included, as should emissions of CO_2, methane and nitrous oxide from biomass storage (Jämsén et al. 2015; Routa et al. 2016).

The impacts of bioenergy systems on atmospheric GHG concentrations are determined largely by how the carbon cycle is affected by the biomass supply system, how efficiently biomass is converted to energy products, the GHG-intensity of the bioenergy supply chain and of the energy product displaced, and the efficacy of any carbon capture and storage, through biochar or post-combustion treatment.

BOX 1 | Reporting and accounting for bioenergy in national greenhouse gas (GHG) inventories.

Countries report their national inventory of annual GHG emissions and removals under the United Nations Framework Convention on Climate Change (UNFCCC), following guidelines developed by the Intergovernmental Panel on Climate Change (IPCC). For UNFCCC reporting, biogenic CO_2 emissions from bioenergy are counted as zero in the energy sector to avoid double-counting because biogenic CO_2 emissions from the harvest of biomass are included in carbon stock changes counted in the Land Use, Land use change and Forestry (LULUCF) sector (Houghton et al. 1997; Goodwin et al. 2019). Consequently, if all countries follow these guidelines and report to the UNFCCC, all emissions from the use of biomass for energy will be included in national inventories. Under the Kyoto Protocol only developed ('Annex I') countries had commitments and were required to account for their emissions against agreed targets. Any decline in forest carbon associated with harvest for biomass in non-annex 1 countries, including biomass exported to annex 1 countries, was excluded from accounting. Furthermore, reporting changes in forest carbon stock was optional for annex I countries in the first commitment period (2008–2012), and there was limited incentive to enhance forest carbon stocks due to national caps on forest sinks. These deficiencies were partly addressed for the second commitment period (2013–2020), in which accounting for 'forest management' became mandatory for annex 1 countries. However, forest management emissions and removals were accounted relative to country-specific, projected reference levels representing the 'business as usual' baseline, so harvesting of biomass only counted as a debit if it was not included in the agreed 'forest management reference level'.

Under the Paris Agreement, the EU, through Regulation 2018/841 of the EU Climate and Energy Framework (Camia et al. 2020), sought to avoid the loophole of unverified counterfactuals by basing its forest management reference level on continuation of historical forest management (Grassi et al. 2018). As regards accounting for CO_2 emissions and removals associated with forest products including bioenergy, countries may apply one of four approaches reflecting different system boundaries (i.e., stock-change, production, simple decay or atmospheric flow approach IPCC 2006; IPCC 2019). Thus, emissions associated with bioenergy may be reported by the producing or consuming country and may be based on carbon stock change in the forest or in the wood products pool, depending on the approach chosen (Rüter et al. 2019). The approach selected will influence the country-specific incentives for domestic use and trade in wood products including bioenergy (Cowie et al. 2006, 2021; Pingoud et al. 2010), and the inconsistency in methods creates potential for omissions and double-counting (Sato and Nojiri 2019). Nevertheless, irrespective of the accounting approach chosen, all countries are required to provide supplementary information on emissions and removals from harvested wood products estimated using the production approach to aid transparency (UNFCCC 2018).

2.3 | Key Issues for Forest-Based Bioenergy

In this paper, forest-based bioenergy refers to biomass derived from forests (naturally regenerated or plantations) that are managed on a rotation of at least 10 years, including by continuous cover forestry. Short rotation woody crops that are harvested every 1–5 years are more similar to agricultural crops (Section 2.4) with respect to the quantification of climate effects.

In industrialised countries, forest-based bioenergy is commonly a co-product of the forest industry, associated with the production of wood products (sawn timber, composite products, pulp and paper) (e.g., Koponen et al. 2015, figure 23; Luke 2024a). In developing countries, fuelwood is commonly harvested for household uses, independent of forestry activities. Common bioenergy feedstocks include harvest residues (i.e., branches, tops, stumps), residues from wood processing (e.g., sawdust or shavings from sawmills, black liquor from pulp processing), construction waste or end-of-life wood products and small diameter roundwood from thinnings in forests managed for sawlog production. Forest management choices (species, silviculture, rotation length, clear-fell or continuous cover) affect the carbon stocks, growth rates and quantities and proportions of different primary forest products available for harvest (Pingoud et al. 2018; Vauhkonen and Packalen 2019). Biomass for energy has traditionally had a low economic value compared with other wood products, so bioenergy has not usually been the primary driver determining forest management and harvest scheduling. However, in recent years, the price of bioenergy feedstock has increased in some regions, for example, due to increased demand for energy wood, an increase in emission trading prices and geopolitical and market changes (e.g., in Finland and Sweden, Luke 2024b; Energimyndigheten 2024). Bioenergy's influence on forest management needs to be assessed in the context of regional forest product markets, including management responses to anticipated demand for bioenergy (Costanza et al. 2017; Lamers et al. 2018; Parish et al. 2017; Daigneault et al. 2022; Favero et al. 2023).

The life cycle of forest-based bioenergy is complex due to decadal rotation periods, intermediate harvests (e.g., thinning) and potentially long lifetimes and varying substitution effects of wood co-products. The carbon stocks and sink strength of individual stands vary widely between young and mature stages (Figure 1a). A forest estate is a mosaic of stands of different ages shaped by biophysical factors such as soil and climate conditions, historical and current management and harvesting regimes and events such as storms, droughts and forest fires. Across a forest estate, stands are harvested sequentially to produce a continuous supply of wood for the forest industry. In a 'normal forest' (ideal forest with equal areas of each age class; Leslie 1966), the carbon losses through stand harvest are balanced by gains in the other stands, resulting in constant carbon stock across the estate (Figure 1b). In reality, forest estates commonly have an uneven distribution of age classes, so carbon stock fluctuates around a trend line showing gradually increasing, decreasing or roughly stable total carbon stock. Forest management operations (fertilising, thinning and pruning), rotation length and species mix influence carbon stocks and sink strength, which are also strongly influenced by environmental factors including climate, soil properties and atmospheric CO_2 concentration (Henttonen et al. 2017). Furthermore, forest carbon stocks are also affected by natural disturbances such as drought, fire, storms and pests, which will likely increase due to climate change (Nabuurs et al. 2022).

A key aspect governing the climate effect of bioenergy is the influence of biomass extraction on the carbon stock in vegetation and soil. Introduction of a new management regime that involves more biomass extraction (e.g., removal of logging residues) can reduce the average carbon stock in the forest compared to a

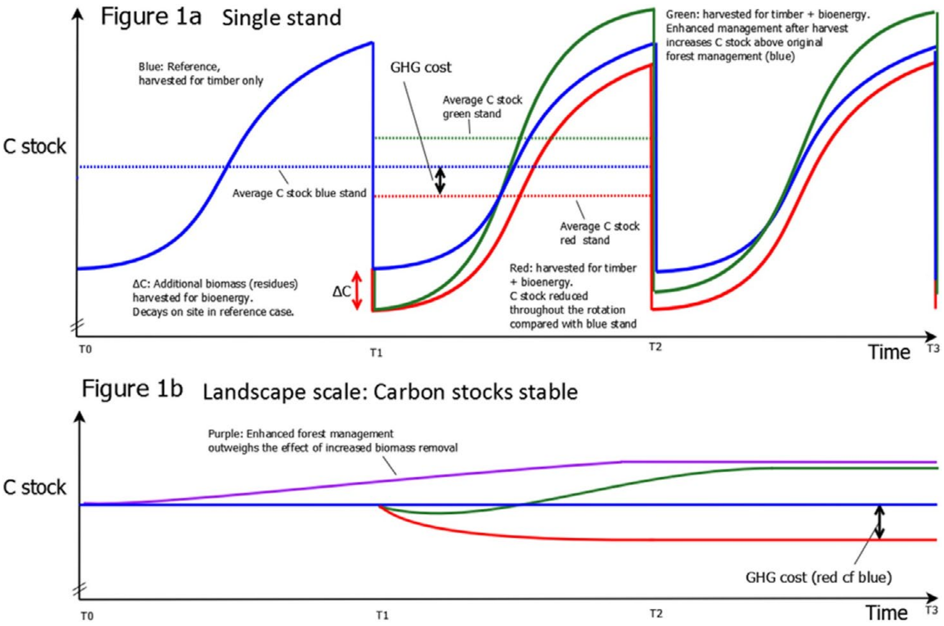


FIGURE 1 | Theoretical representation of the carbon stocks in a managed forest, illustrating a single stand (a) and a forest estate with an even distribution of age classes (b). Key: Blue: Reference scenario, a forest harvested for timber only, with residues (branches and tops) retained in the forest; Red: Harvest residues removed for bioenergy; Green: Harvest residues removed for bioenergy with enhanced management applied after harvest; Purple: Harvest residues removed for bioenergy before harvest. *Source:* Cowie et al. (2013).

reference scenario with less biomass extraction, signifying a net biogenic carbon emission, a 'GHG cost' (in Figure 1, red curves). However, if growth-enhancing measures (e.g., improved site preparation, genetic material, fertilisation) and modified harvest schedules are also introduced that simultaneously increase forest carbon stock (in Figure 1, green and purple curves), this can reduce or avoid the GHG cost of increased biomass extraction, noting that growth-enhancing measures will take time to affect slow-growing forests.

As described above, wide temporal variations in emissions and removals apparent at stand level are smoothed when considered at landscape level. Nevertheless, as at stand level, additional extraction of biomass for bioenergy can lead to a decline in average carbon stock, creating a 'GHG cost' in forest carbon balance compared to a reference scenario with less biomass harvest (Figure 1). If the GHG cost is lower than the avoided fossil CO_2 emissions, there will be an immediate benefit, such as when residues that would otherwise have decayed quickly are used efficiently to substitute fossil fuels (e.g., Agostini et al. 2013; Matthews et al. 2014). However, if bioenergy leads to a reduction in forest carbon stock, compared to the reference scenario, such as through increased harvest intensity, a forest bioenergy system could cause net emissions for decades (Pingoud et al. 2016), despite providing emission savings in the longer term (e.g., Hudiburg et al. 2011).

Thus, in quantifying the climate effects of forest-based bioenergy, it is necessary to consider all the effects of forest-based bioenergy on carbon stocks in forests, harvested wood products and fossil resources over the relevant time horizon given by the aim of the study (see Section 2.5), including, if relevant, accelerated planting of new productive forest as a response to anticipated future demand for bioenergy. As the effects are quantified based on a comparison with a reference scenario, the definition of this reference has a critical influence on the results (see Section 3.4).

2.4 | Bioenergy From Agricultural Systems

Agricultural sources of biomass for bioenergy include purpose-grown crops (e.g., canola, sugar cane, switchgrass, miscanthus), agricultural production residues (e.g., straw, manure) and processing residues (e.g., rice husk, nut shells). As for forestry, bioenergy from agricultural sources should be assessed as a component of agricultural systems.

The climate effects of bioenergy from agricultural systems tend to be easier to evaluate than forest-based bioenergy because the crops are generally harvested annually or on a short rotation of several years, so the wide variation in carbon stocks seen in forest stands, discussed in Section 2.3, is not applicable. Therefore, the timing of emissions and removals (Sections 2.5 and 3.4.2) is generally not a significant issue, as demonstrated by Brandão et al. (2019), and it is generally accepted (e.g., IPCC 2019; ISO 2018) that biogenic carbon fluxes of non-woody crops are excluded in quantifying GHG inventories. Nonetheless, iLUC (see Section 3.2.3) and counterfactual land use (Section 3.4) are equally relevant for agricultural systems as for forestry systems, and quantifying these faces the same challenges and uncertainties.

The removal of crop residues for bioenergy could cause loss of soil carbon. Similarly, the expansion of energy crops could result in GHG emissions due to loss of vegetation or soil carbon if pastures or natural areas are converted to cropping. On the other hand, the establishment of biomass crops such as perennial grasses on cropland that has been depleted of soil organic matter can lead to gains in soil and vegetation carbon stocks. Soil carbon changes tend to be case-specific, presenting challenges of data availability, and while often small, they can be significant for LCA results (Bessou et al. 2020). If existing cropland is used for energy crops, displacing food production, this could impact food security or lead to indirect intensification of food production or land use change such as deforestation, with potential negative impacts on carbon stocks and biodiversity (Searchinger et al. 2008; Tonini et al. 2016). Achieving high yields from energy crops may require high rates of nitrogen fertiliser, with associated GHG emissions from fertiliser manufacture and N_2O emissions from soil (e.g., Smith et al. 2012). Conversely, utilising manure for bioenergy, such as through anaerobic digestion, can reduce methane emissions from manure management and generate a nutrient-rich soil amendment from the digestate, which can displace more synthetic nitrogen than untreated manure.

Thus, as for forest-based bioenergy, the methods used to estimate climate effects of agricultural bioenergy need to acknowledge positive and negative effects on GHG emissions due to changes in vegetation and soil C stocks, non-CO_2 GHG emissions and production of agricultural commodities and the related market effects.

2.5 | Timing of Emissions and Removals

To limit warming to 1.5°C with minimal overshoot, global net zero CO_2 needs to be reached in the early 2050s (IPCC 2022). The IPCC has quantified the remaining global carbon budget consistent with limiting warming to 1.5°C or 2°C, representing the cumulative GHG emissions from 2020 until net zero CO_2 is reached (Rogelj et al. 2018). The exact timing of CO_2 emissions and removals is less important than the cumulative total CO_2 emissions due to the long-lasting effect of CO_2 on climate (IPCC 2021). As discussed in Section 2.3, bioenergy systems could cause an increase in emissions varying from years to decades if land carbon stock is reduced by a greater amount than the emissions saved by displacing fossil fuels. If the reduction in carbon stock is temporary and reversed through the re-accumulation of carbon before net zero CO_2 is reached, this does not consume the carbon budget and has a net climate impact similar to short-lived climate forcers (Cherubini et al. 2014). However, if there is a consistent long-term reduction in land carbon stock (a reduction in the equilibrium value) in the bioenergy system, this is equivalent to CO_2 emissions from fossil sources, and does expend the carbon budget, unless the biogenic CO_2 is captured and stored in geological reservoirs.

A short-term emissions increase can be considered a 'GHG investment' in establishing a bioenergy system, equivalent to fossil CO_2 emissions released when building a railway or producing batteries for electric vehicles (Berndes et al. 2010); but the bioenergy system must deliver emissions savings through fossil fuel displacement within the relevant temporal window to avoid contributing to peak warming. The definition of this relevant temporal window remains contested (Allen 2019; Asayama et al. 2019; Rogelj et al. 2018). Nevertheless, with growing recognition of the limited carbon budget and concerns about reliance on carbon removals after an emission overshoot (Schleussner et al. 2024), ambitious short-term emissions reduction targets are being adopted by countries and businesses. This reduces the attractiveness of options with up-front emissions that cause a delay in achieving net GHG savings. However, options with low up-front emissions may be restricted by immature development, high cost or dependence on new infrastructure, so focusing only on such options could prolong fossil fuel use; the definition of the relevant temporal window is critical also for such options.

Due to relatively long economic lifetimes of energy infrastructure and long rotation times, especially in boreal forests, decisions today will have long-term impacts on emissions and removals (IPCC 2014, 2022). Bioenergy can be deployed rapidly as it is compatible with existing energy infrastructure and cost competitive in many applications. Parallel deployment of carbon capture and storage from bioenergy systems, that is, BECCS, could markedly change the balance and timing of emissions and removals (see Section 3.4.3). Furthermore, bioenergy systems can support expansion of variable renewable electricity production from wind and solar power through the provision of balancing power needed to maintain power stability and quality (Thrän et al. 2024; Arasto et al. 2017; Hakkarainen et al. 2019; Lenzen et al. 2016), thereby contributing to the transformation to a low-GHG electricity system and delivering emissions savings across the whole energy system in the short and long terms (e.g., Li et al. 2022, 2024). Bioenergy investments could displace investments in new fossil fuel infrastructure, avoiding consequent ongoing emissions. On the other hand, bioenergy deployment through co-firing biomass with fossil fuels could slow the phase-out of fossil energy infrastructure. Whether such development is compatible with climate targets depends on the proportion of biomass to fossil fuels and the degree to which carbon capture and storage is deployed.

Thus, the issue of the timing of emissions, removals and displacement benefits associated with the deployment of bioenergy is complex: both the contribution to near-term emissions reduction targets and to long-term temperature stabilisation can be relevant, and it is important to consider broader energy system implications from the expansion of bioenergy. Conventionally, in LCA, the timing of emissions and removals is not considered: the climate impact, or carbon footprint, of a product is calculated by summing the emissions over the entire life cycle with equal weight regardless of when the emissions occur (e.g., Brandão et al. 2013; ISO 2018). However, there is increasing recognition that timing can be significant; although there is no consensus on how it should be included in LCA. Methods that recognise effects of time are discussed further in Section 3.4.2.

3 | Aspects to Consider in Quantifying the Climate Effects of Bioenergy

This section describes the methodological choices that influence the quantification of climate effects of bioenergy and provides guidance on the selection of methodology appropriate to the application.

3.1 | Functional Unit

LCA is generally applied at product level and used to calculate and compare the impacts of different technologies to generate the same functional unit. The functional unit is the reference against which inputs and outputs are normalised. The choice of functional unit is critical, as different functional units can lead to different conclusions (Cherubini et al. 2013). To facilitate comparison between energy products, the climate effect is expressed using a unit of energy product or service as the functional unit, for example, gCO_2e per MJ energy delivered, or gCO_2e per km travelled in standard passenger vehicle (ISO 2018). Additionally, it can be pertinent, especially to resource managers, to quantify the emissions saved per unit of biomass resource consumed, or per unit land area used for biomass production (Cherubini et al. 2013), for both bioenergy and BECCS. Additionally, in the case of BECCS, relevant measures are also the emissions per unit of carbon dioxide removal (CDR) delivered, and CDR delivered per unit biomass, noting the importance of appropriate handling of co-products (see Section 3.4.3). While LCA is usually focussed on a specific product, it is possible to use a much broader functional unit, such as the energy supply for a province, a country or a wider region, which allows constraints on availability of biomass to be included. This broad scale may be most relevant to policy-makers, especially when applying consequential LCA (see Section 3.2).

3.2 | Modelling Approach

3.2.1 | Attributional vs. Consequential LCA

LCA has been categorised into two modelling approaches, namely attributional LCA (ALCA) and consequential LCA (CLCA). Various definitions for ALCA and CLCA have been proposed, and the two approaches have been applied inconsistently in the scientific literature (Soimakallio et al. 2015; Zamagni et al. 2012). The choice of modelling approach has a large impact on the result (Brandão et al. 2021; Pereira et al. 2019).

In ALCA, inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule (UNEP/SETAC 2011). ALCA focuses on describing all the environmentally relevant physical flows (such as greenhouse gas fluxes) to and from a product system over its life cycle (Curran et al. 2005; Finnveden et al. 2009). It aims to describe the environmental impacts of a system as a component of the total impact of all human activities (Soimakallio et al. 2015), typically using average historical data. Conversely, CLCA aims to describe how environmentally relevant physical flows respond to a change (Finnveden et al. 2009), such as increased production of bioenergy. Therefore, in CLCA, activities are included in the product system to the extent that they would change (or have changed) as a consequence of a change in demand for the functional unit (UNEP/SETAC 2011). To inform policy on bioenergy targets, CLCA could be used, for example, to examine the climate effects of increasing a biofuel mandate from 10% to 30%, whereby the functional unit represents all supply changes associated with meeting this mandate. CLCA thus captures the direct and indirect consequences of decisions, including market-mediated effects due to change in the level of production. Typically, average data are applied in ALCA, whereas marginal or incremental data are applied in CLCA (Finnveden et al. 2009) (Brandão et al. 2022). Guidance on application of CLCA to bioenergy systems is provided in Brandão, Weidema, et al. (2024).

The most appropriate modelling approach depends on the purpose (Brandão, Busch, and Kendall 2024). When considering the climate effects of one bioenergy product in the prevailing or assumed economic conditions, independent from market responses, an attributional modelling perspective is adequate. ALCA is therefore commonly applied in micro-scale product comparison (EC-JRC-IES 2010), in assessing compliance with regulations and for product declarations, but is insufficient for guiding policy decisions (Brandão et al. 2014; Plevin et al. 2014) or understanding the consequences of increased or decreased use of bioenergy. LCA studies undertaken to inform policy decisions relating to, for example, scale of bioenergy targets or prioritisation of biomass use for competing energy and materials, should use a consequential approach, which considers indirect effects in the land, food, forest products and energy sectors as well as socio-economic and biogeophysical effects (EC-JRC-IES 2010). See also Section 3.2.3.

3.2.2 | Handling Co-Products

If a bioenergy product is derived from a system with several outputs or functions, a method must be used to isolate the impacts belonging to bioenergy. The ISO standard for LCA presents a hierarchy of options, giving priority to avoiding allocation by subdivision or system expansion (ISO 2006a) (Box 2). System expansion (with substitution) follows consequential logic, giving credit to the product under study for products displaced by the co-products (Figure 2). In ALCA, allocation based on an attribute such as energy content, mass or value is the basis for sharing impacts. The ISO standard recommends using a procedure that reflects underlying physical properties, ahead of economic allocation as the last option in the hierarchy. Choice of attribute can have a strong impact on the result (e.g., Wardenaar et al. 2012; Cherubini, Strømman, et al. 2011). Despite being least favoured in the ISO hierarchy, economic allocation is often recommended as reflecting causality for the decision to co-produce. Mass allocation can be misleading where the by-product has greater proportional mass than the determining product, and energy content makes little sense if the co-product is not an energy source (e.g., canola meal co-produced with canola oil). Any allocation choice is subjective, and allocation inevitably results in allocated systems that do not balance inputs and outputs (Weidema and Schmidt 2010). Nevertheless, allocation rules can be useful for policy implementation, to provide consistency and certainty to industry, and agreed allocation approaches could be established through product category rules developed through transparent and participatory processes.

BOX 2 | Treatment of co-products.

The life cycle assessment standard ISO 14044 presents the following hierarchy for treatment of co-products:

1. Where possible, avoid allocation by
    a. subdivision: Divide the product system into sub-processes, such that inputs and outputs specific to the studied co-product are separated
    b. system expansion with substitution: Expand the system boundary to include all functions related to co-products (see below)
2. Allocation: Share inputs and outputs between co-products on the basis of
    a. underlying physical relationship (such as energy content)
    b. other relationship such as economic value of co-products

Co-products from a multi-output system can displace other products, generating additional mitigation (Soimakallio et al. 2016), such as when biochar, a co-product of pyrolysis or gasification, is used as a soil amendment that improves nitrogen use efficiency, thereby reducing fertiliser requirements (Cowie et al. 2015). Applying CLCA in this example, the avoidance of emissions from fertiliser manufacture would be credited to the bioenergy system. In such studies, the sensitivity of assumptions made on displacement needs to be considered.

3.2.2.1 | System Expansion, With Substitution.

System expansion involves expanding the modelling to include the fate of the co-product (Product B in Figure 2) in addition to the bioenergy product (Product A). To determine the climate effect of Product A, the total GHG emissions and removals of the multi-functional activity (Products A and B) are included and the GHG emissions and removals of a displaced alternative product (Product C, functionally equivalent to Product B) are subtracted.

3.2.3 | Indirect Effects

Indirect effects, both within the bioenergy system supply chain and beyond, can influence the climate effects of bioenergy. If land use changes from food production to a dedicated bioenergy crop, land use elsewhere might change to meet the demand for

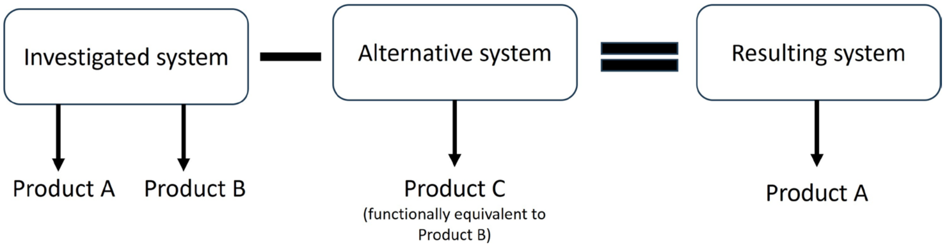


FIGURE 2 | System expansion with substitution, to determine the effect of producing Product A. Adapted from ISO 13065 (ISO 2015).

food. Emissions associated with this indirect land use change (iLUC) can diminish the net climate benefits of bioenergy particularly if high carbon stock land is converted to food production. Estimates of the magnitude of iLUC vary widely between studies (Ahlgren and Di Lucia 2014; Brandão 2022; de Carvalho Macedo et al. 2015), partly because iLUC, by definition, cannot be verified or ascribed to a specific bioenergy system, and because different methods and assumptions have been used to quantify it (Searchinger et al. 2015; De Rosa et al. 2016; Langeveld et al. 2022).

Use of biomass for energy can also have indirect market-mediated effects on the production and use of other bio-based products. As forest-based bioenergy and wood products are interrelated industries, one might expect increased use of forest biomass for energy to reduce supply of other wood products. However, global modelling by Daigneault et al. (2022) indicated the potential for simultaneous increase in forest C stocks and wood harvest through stimulation of improved forest management, and others have determined that increased demand for bioenergy led to forest expansion (Galik and Abt 2016) and retention of forests that would otherwise have been cleared for farmland (Hodges et al. 2019). These studies indicate synergies between bioenergy demand and supply of wood products that are revealed when economic factors and management responses are considered.

GHG savings from substituting concrete, steel and aluminium building elements with wood, synthetic textiles with cellulose-based materials or fossil-based plastics with wood–plastic composites may be significantly larger than substituting fossil fuels by bioenergy (Hurmekoski et al. 2020; Kurz et al. 2016; Sathre and O'Connor 2010). Cascading use of biomass, first for materials and subsequently for energy, can generate higher GHG benefits through multiple substitutions compared with direct use of newly harvested wood for energy (Gustavsson et al. 2006; Pingoud et al. 2010; Höglmeier et al. 2015), but strict application of cascading principles could constrain the availability of wood for energy (Bais-Moleman et al. 2018). The wide variety of wood products and displaced construction materials make it difficult to generalise the substitution value of wood products (Myllyviita et al. 2021; Kunttu et al. 2021; Hurmekoski et al. 2021; Niemi et al. 2025), and modelling choices also impact results (Piccardo and Gustavsson 2021). Thus, the indirect effects of bioenergy on wood products can be challenging to assess. The phenomenon of rebound should also be acknowledged, and due to impacts of bioenergy on prices of fossil fuels, bioenergy does not necessarily displace the same amount of fossil fuel energy products (Smeets et al. 2014).

Estimation of the indirect consequences of bioenergy, including indirect market-mediated effects especially iLUC, is important in CLCA, especially when used to inform policy development. Studies on this topic apply general or partial equilibrium modelling (e.g., Zhao, Taheripour, et al. 2021) or biophysical models that link demand for land with physical data on crop yields and statistical data on land-use changes (e.g., Schmidt et al. 2015). Alternative modelling approaches, reflecting contrasting narratives on the causes and therefore appropriate analytical approaches to quantifying iLUC, lead to divergent results (Malins 2019; Langeveld et al. 2022). Approaches to recognise iLUC in ALCA-based assessments include addition of an 'iLUC factor' (e.g., European Union 2018, annex VIII; ICAO 2022), noting that their quantification is highly uncertain (Daioglou et al. 2020; Malins et al. 2020), and effectiveness of such factors in policy implementation is questioned (Khanna et al. 2017). Alternative approaches to manage iLUC in policy implementation include application of a risk-based approach that permits only feedstocks deemed to have low iLUC risk (RSB 2018; European Union 2018; Sumfleth et al. 2020).

3.2.4 | Other Modelling Approaches

Expanding the system boundary of an assessment beyond the supply chain can help quantify additional impacts indirectly related to the system that occur within a sector, economy or supra-regional level. For example, these effects can be assessed using life cycle-based environmentally extended input–output (EEIO) modelling (Leontief 1970). EEIO models use sectoral, national or global economic structures, described in the form of make-use or input–output tables (such as developed by national statistical offices) and link these with emissions databases such as national emission inventories (Yang et al. 2017). EEIO modelling is a data-intensive process, yet it enables the user to assess the effects of a specific subactivity, such as biofuel production, within the context of the remaining sectoral, national or global activities and provide results across environmental and socio-economic dimensions (Avelino et al. 2021). It also allows the calculation of net effects, for example, the quantification of the effects related to an expanding bioeconomy, displacing incumbent petroleum-based fuels or products (Avelino et al. 2021; Lamers et al. 2021). Applying a prospective EEIO framework can further illustrate these net effects under changing consumption or production patterns and other macro-economic factors (e.g., population trends, inflation).

A further system boundary expansion can be achieved by linking LCA with integrated assessment models (IAM). IAMs encompass biophysical (biosphere and atmosphere processes) and socio-economic flows at national, regional and global scale to explore the future evolution of the global energy, land, economy and climate system (IAMC 2020). IAMs are prominently used to support long-term climate change assessments to explore the solution space of different climate policy interventions (IPCC 2022). The utilisation of the rich system-level dynamics of IAMs to inform the background processes in LCA was directly linked to development of code-based LCA (Mutel 2017). The code structure enables the computation of interconnected time-series LCI7 databases, which form the basis for the calculation of time-step LCA, accounting for a suite of background dynamics represented in IAM scenarios (Beltran et al. 2020). With the availability of open-source code options to utilise scenarios from several IAMs (Sacchi et al. 2022; Lamers et al. 2023; Ghosh et al. 2024), the use of IAM-LCA to inform economy-wide shifts or sectoral transitions accounting for interactions with the land sector, for instance, has gained much prominence in the scientific literature (Cavalett et al. 2024; Ballal et al. 2023; Gvein et al. 2023). One critical research frontier in IAM-LCA linkage is to use LCA impact metrics to re-inform IAM scenarios and thus create projections that solve beyond cost and carbon as the key metrics.

The representation of bioenergy systems in IAMs tends to be coarse, with respect to spatial resolution, and limited, with respect to feedstocks and field management practices, conversion technologies, influence of land quality, and overlooks effects of biomass extraction on nutrients and water (Rose et al. 2022). IAMs therefore provide information on potential contribution of bioenergy to climate change mitigation under different socio-economic development pathways, under different climate goals, but they do not provide information that enables detailed comparisons of the climate and other environmental impacts of different technologies and bioenergy systems.

To understand and optimise the role of bioenergy and BECCS as a part of specific regional or local energy system, various energy system modelling approaches with focus on long-term planning or short-term operation can be applied (Laveneziana et al. 2023). These models have narrower system boundary than IAMs but they provide a more detailed description of the studied energy system, and the technologies applied. Energy system models can also be combined with biomass supply models (Lindroos et al. 2021) or coupled with LCA to assess several impact categories beyond GHG emissions (Blanco et al. 2020). These integrated approaches can be used to evaluate system-level emissions. Arguments have been made for using more than one approach whereby top-down approaches, like economic input–output data, IAMs and economic general equilibrium models, can be complemented with bottom-up approaches, like LCA (Creutzig et al. 2012). Especially when planning for bioenergy and BECCS policies, it is recommended that several approaches are applied, and impact categories beyond climate are analysed (Koponen et al. 2024).

3.3 | System Boundary

The system boundary describes the activities and processes that are quantified in the system under study. Key processes and activities in the bioenergy system include production of fertiliser, site preparation/crop cultivation, fertiliser application, harvesting, transport, processing to energy products, distribution of energy product and co-products, combustion and waste disposal. Key aspects of the system boundary for bioenergy systems that influence the results of assessment include the spatial and temporal boundaries, discussed below.

3.3.1 | Spatial Boundary and Scale

The spatial boundary of the study affects the results particularly in the case of forest-based bioenergy derived from long-rotation forestry (Cintas et al. 2017). Considered at a stand level, the asynchrony between emissions and sequestration suggests that during the period between combustion and regrowth, there is additional CO_2 in the atmosphere, causing warming. However, at forest estate (landscape) level, the temporal fluctuations are smoothed, as explained in Section 2.3, and if harvest equals annual increment, there is no delay between absolute emissions and removals.

The appropriate spatial boundary is determined by the purpose of the investigation. For example, a policy-maker may be concerned with the impacts at a regional or national scale, so assessments to inform such policy development should take place at that broad scale (e.g., Cintas et al. 2017). Here, the effects of bioenergy policy on land use, including expansion or contraction of forest area, are relevant. On the other hand, a forest owner or farmer would be interested in effects at the farm or forest estate level, while assessment undertaken for product labelling should use the scale of analysis that applies to the system producing that product.

The location and scale impact the results of assessments due to the geographic variation in factors such as climatic conditions, forest or crop management practices and soil properties that influence growth rates and yields as well as aspects such as soil carbon and vegetation loss if there is land use change. Thus, care should be taken when generalising from the results of studies elsewhere or applying regional- or national-level data for farm or forest-level studies (e.g., Bontinck et al. 2020).

In the case of national inventories, annual emissions and removals are quantified within territorial boundaries (Box 2), and spatial boundaries should be applied consistently to reduce leakage (increase in emissions resulting indirectly from mitigation activities) and double-counting. In contrast to the territorial boundary of national inventories, LCA applies a life cycle boundary that includes upstream and downstream emissions and removals, wherever they occur. The spatial boundary of an LCA may be narrow or very wide, depending on the definition and type of LCA. Thus, it is important to clearly state the purpose of the LCA and define the spatial boundaries accordingly. To aid interpretation and inform management decisions, direct and indirect effects should be separated when presenting the results of analyses. The results of local scale LCA should not be assumed to apply at large scale nor inferred to describe large-scale dynamics or policy impacts. Likewise, global or national average results should not be assumed to apply to individual projects.

3.3.2 | Temporal Boundary

In LCA, the assessment starts at the 'cradle', which commonly includes raw material extraction, and ends at the 'grave' (end use, i.e., combustion and disposal of any wastes), although in the case of bioenergy (and other agricultural and forestry products) a partial life cycle is often quantified, from 'cradle to gate', that is, including production and processing, but excluding transport to the consumer, use and disposal. For forest-based bioenergy, the assessment could commence when the forest was planted, or at the time of harvest, leading to very different conclusions (Koponen et al. 2018; Albers et al. 2019, Soimakallio et al. 2025). If the biomass is produced from reforestation undertaken to meet bioenergy demand, then the initial growth is commonly included at the start of the bioenergy life cycle (e.g., Han et al. 2018). Forster et al. (2021) applied prospective LCA with a 100-year time horizon into the future to explore the climate effects of forest planting decisions in the context of national afforestation targets, considering the effect of, *inter alia*, species choice, cascading uses of harvested wood and replanting. If forest management is changed in advance of the first harvest, with the specific purpose to increase biomass for bioenergy, such as by skipping pre-commercial thinning, it may be appropriate to start the assessment at the time management was changed. However, often, there is interest in the impacts of an upcoming decision whether to harvest, independent of prior management decisions. For example, to assess the impacts of a policy decision to increase the harvests from existing forests for bioenergy, the effects from the time of its announcement describe the impact of the policy. Consequently, retrospective and prospective perspectives may both be relevant, depending on the goal of the study (Albers et al. 2019). Where there is land use change to establish a bioenergy crop associated with the goal and scope of a study, the temporal boundary includes land conversion, for example, from pasture or natural vegetation, and the associated change in soil and vegetation carbon stocks.

To quantify the change in land carbon stocks resulting from a land use change or change in management of a forest or agricultural system to supply biomass for bioenergy, at least one rotation (for long rotation forests) or several rotation cycles (for short rotation woody crops and annual crops) should be considered. This recognises that impacts on the soil carbon pool can take decades to reach a new equilibrium if there is a change in biomass inputs and also allows for inter-annual variability in biomass growth due to seasonal variation in climatic conditions, common in dryland regions. Land carbon losses may prevail for decades but can also shift to land carbon gains, depending on ecosystem characteristics and how land use practices change over time (Cintas et al. 2016). Data need to be collected or modelled consistent with the chosen temporal boundary, to enable calculation of average carbon stocks in vegetation and soils in the bioenergy system and reference land use system.

Emissions avoided by fossil fuel displacement accumulate over time as more biomass displaces more fossil fuels. Although decarbonisation of energy systems, which reduces the GHG intensity of electricity services, could reduce the displacement benefit of bioenergy over time, bioenergy products are likely to provide substantial mitigation by continuing to displace fossil fuels, as discussed in Section 3.4.

Any initial carbon cost resulting from land use change or change in land management diminishes as it is averaged over a longer period providing more energy services. The time frame chosen to assess the climate effects has a significant impact on the results and can even reverse the conclusions drawn (e.g., Gustavsson et al. 2021). Forestry systems are commonly assessed over a 100-year period, or longer in boreal regions with long rotation periods, but shorter timeframes (20 or 50 years) can be relevant to short- and medium-term emission reduction targets. Landholders and investors may be interested in analysis over the anticipated lifetime of a project or bioenergy production facility.

3.4 | Reference System

To determine the full climate change effects of bioenergy, the bioenergy system must be compared with a reference “without bioenergy” scenario, or counterfactual, that describes the land use and energy source that would apply in the absence of bioenergy (Figure 3) (Schlamadinger et al. 1997; Cherubini et al. 2009; Koponen et al. 2018; Cowie et al. 2021). The temporal boundary should recognise: dynamic biogenic carbon flux patterns, for example, modeling over several forest or crop rotations; the trajectory for energy system transition and short- and long-term climate objectives coherently with the goal and scope of the study.

3.4.1 | Reference Land Use

Comparison with the reference land use allows the inclusion of impacts of change in land use or land management on C stock in vegetation and soil. As with the bioenergy system, it is important to consider the influence of both management and natural factors. In the case of forests, the reference scenario may include forest management for a different mix of products and services, different intensity of harvest or preserving the forest for conservation. In situations where, without the bioenergy system, the trees would have continued to grow, or less intensive harvest would have been applied, the bioenergy scenario can be considered to incur forgone C sequestration (Agostini et al. 2013; Kallio et al. 2013; Koponen and Soimakallio 2015; Matthews et al. 2014; Sievänen et al. 2014; Soimakallio et al. 2016). In assessing forgone sequestration, it should be recognised that sequestration rates are non-linear and there are uncertainties involved in the development of forest carbon stocks in both ‘with bioenergy’ and ‘without bioenergy’ scenarios (Ximenes et al. 2012). Due to uncertainties in projecting future growth and land management, it can be instructive to consider several alternative reference land use scenarios, particularly to inform policy. The relevant reference land use will be determined by the purpose of the analysis: if the goal is to quantify the contribution of bioenergy as a component of all human activities (ALCA), natural regeneration is the appropriate reference, whereas if the goal is to estimate the effect of increasing bioenergy (CLCA), the most likely alternative land use is the valid reference (Koponen et al. 2018; Soimakallio et al. 2025). If no reference land use is specified, one can only assess the absolute, measurable emissions occurring within a bioenergy system, but not the climate effects attributable to a decision to increase the use of bioenergy (Koponen et al. 2018).

3.4.2 | Reference Energy System

The reference energy scenario should describe the energy source serving the equal function in the absence of bioenergy use for electricity, heat or transport. In ALCA, bio-electricity is typically compared with the GHG intensity of the average electricity mix, representing the market average (e.g., ISO 2018); but in CLCA, the relevant reference energy source is the marginal supply that would be used if the bioenergy was not produced, that is, the source(s) that would respond to an increase in demand for electricity. Where bioenergy displaces fossil fuels, displacing coal generally achieves greater GHG savings than displacing the same energy services delivered by natural gas, as coal typically has a higher GHG intensity than natural gas. The increasing deployment of renewable energy will reduce the GHG intensity of the average electricity mix, but the marginal supply in the electricity grid will depend on the circumstances. In some cases, the alternative to bioenergy is

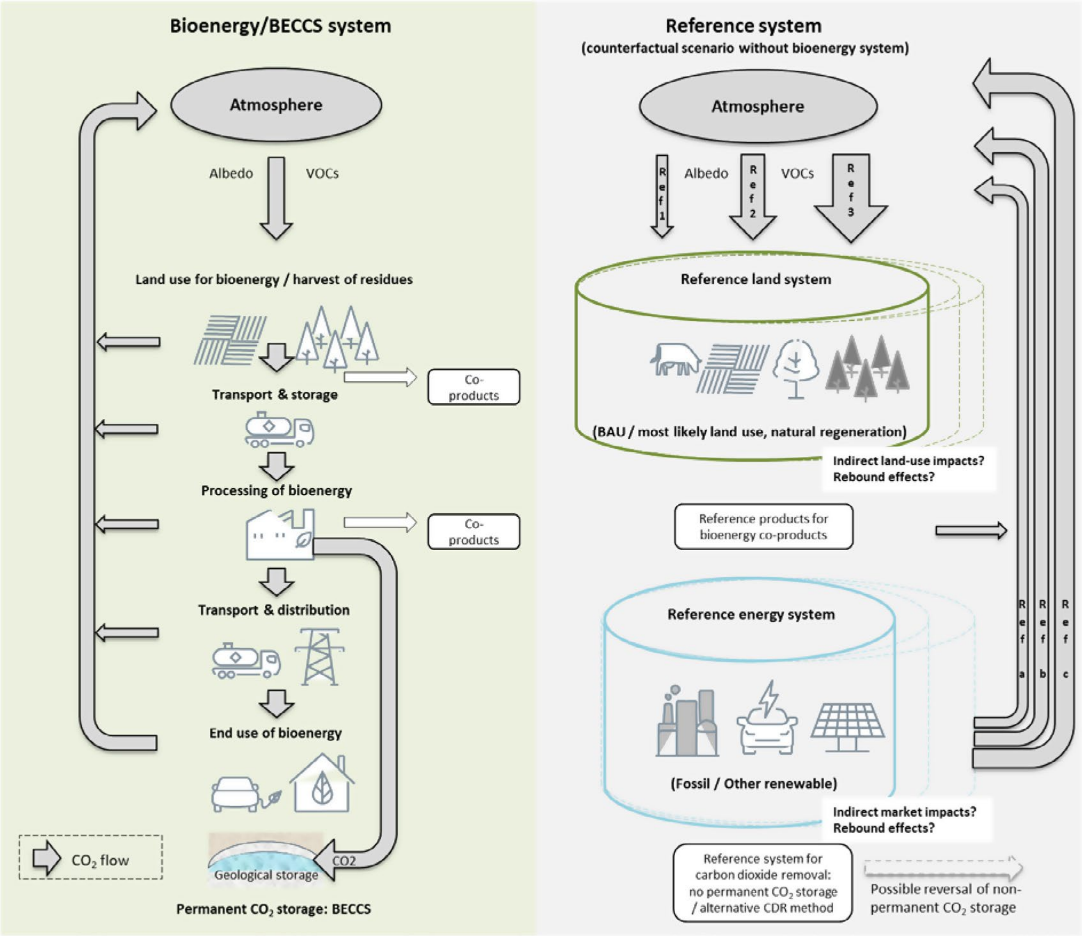


FIGURE 3 | Bioenergy system compared with a reference system representing the situation without the studied bioenergy system. There can be several different land reference systems (Refs. 1, 2, 3) describing, for example, different developments of C stocks in the absence of the bioenergy system, and several different reference energy systems (Refs. a, b, c) describing different substituted products with different emission profiles. If the reference system describes alternative use of resources, indirect market impacts should also be included.

new gas-fired facilities to replace retiring coal (e.g., Bistline and Young 2022). In the heating sector, possible new reference scenarios for bioenergy include electrification, use of heat pumps and waste heat sources (Hiltunen et al. 2025). In the transport sector, e-fuels produced from hydrogen and CO_2 may emerge. In practice, the reference energy system can be difficult to determine objectively (Soimakallio et al. 2011). Flexible use of bioenergy to balance the use of variable renewable energy (wind and solar) may require a more flexible definition of the reference energy system, and the energy system needs to be studied as a whole to capture the total impacts and different roles of various renewable energy production technologies (Holttinen et al. 2025). When analysing BECCS in prospective analyses, an additional consideration is whether displaced fossil fuel systems are also fitted with CCS, which will affect both net energy displacement and the GHG intensity of displaced energy.

3.4.3 | Displacement Value

The mitigation value of utilising bioenergy in place of an alternative energy source will depend on the relative efficiency of conversion to energy products in the bioenergy and reference system, and the relative quantity of GHG emitted per unit of energy product.

The CO_2 emission factor (g CO_2 per GJ of fuel) depends on the chemical composition of the fuel (Cowie et al. 2021). Wood and coal have similar CO_2 emission factors because the relative heating values of the two fuels are similar to the relative carbon content (Koppejan and Van Loo 2012; US EPA 2018; Edwards et al. 2014). Besides heating value, conversion efficiencies also depend on fuel properties including moisture content and grindability (Koppejan and Van Loo 2012; Mun et al. 2016; Yu et al. 2019). The efficiency of conversion of biomass energy to a bioenergy product varies between bioenergy products. For example, the conversion of biomass to liquid biofuels is often less efficient than the direct combustion of biomass for heat or power (Cherubini et al. 2009; Soimakallio et al. 2009; Soimakallio 2014). However, this simple comparison overlooks that as biofuels are more readily stored and transported and can provide a wide range of energy services compared with original biomass, they offer opportunities for displacing hard-to-abate emission sources. Furthermore, the actual displacement effect is determined by market-mediated forces, and indirect market impacts can be important (see Section 3.2.3). For example, implementing a policy to promote the use of biofuels within a certain jurisdiction may influence fuel prices and the consumption of fuels inside and outside that particular area, resulting in changed consumption of fuels compared to the reference system. Consequently, it is unlikely that one unit of fuel displaces exactly one equivalent unit of any alternative fuel in practice, and the displacement share might be both lower and higher than theoretical 1:1 displacement (Rajagopal and Plevin 2013). Net displacement factors could be substantially reduced for BECCS process designs with a high-energy penalty for CO_2 capture (Onarheim et al. 2017). However, there are process designs that avoid energy penalties associated with gas separation (Lyngfelt and Leckner 2015; Zhao, Duan, et al. 2021). Furthermore, the captured biogenic carbon could be used in the production of new products, so biobased products could be associated with multiple substitution events.

Decarbonisation of energy systems through scaling up all renewable energy options will continue to reduce the GHG intensity of energy services, including those associated with bioenergy (Gustavsson et al. 2022). A general trend towards decreasing average GHG intensity of energy services does not necessarily decrease GHG savings through deployment of bioenergy. For example, the electrification of industrial processes will enable the gradual retirement of carbon-based fuel infrastructure; but until fully retired, biofuels can continue to displace fossil fuels. Furthermore, the substitution effects of specific bioenergy products will depend on how the GHG intensities of bioenergy products and alternative products change over time. For example, GHG savings from biofuels substituting petrol and diesel vary significantly because of the large variation in the carbon intensity of crude oil refining (Jing et al. 2020), and future GHG savings will depend on both mitigation actions in crude oil refining and developments in biofuel production, where electrification of biofuel production processes and investments in carbon capture and storage, for example, could bring significant GHG emissions reduction if low-carbon electricity is used.

3.5 | Metrics for Climate Change Impact Assessment

When a pulse of CO_2 is emitted to the atmosphere, a fraction of the CO_2 is taken up by the biosphere, some is dissolved in the ocean, and a large fraction ($>20\%$) remains in the atmosphere indefinitely (Gasser et al. 2017). The climate effect of a pulse emission is quantified as the radiative forcing due to the perturbation in the energy balance of the planet. The commonly applied metric Global Warming Potential (GWP) quantifies the radiative forcing of a GHG pulse emission over a specified time period (commonly 100 years) in comparison with that of a pulse of CO_2 emitted at the same time (Myhre et al. 2013).

Usually in climate change impact assessment in LCA and for GHG inventories, the GWP (100 years) is applied to calculate the CO_2 equivalent (CO_2 eq.) of non-CO_2 GHGs, and the climate effect is quantified as the total of GHG emissions and removals over the entire life cycle (e.g., ISO 2018) or over the first 100 years of the life cycle of a product (e.g., BSI 2011; Han et al. 2018). Only considering cumulative emissions, as when using GWP_{100}, can give misleading results for complex systems with dynamic biogenic emissions patterns (Sathre and Gustavsson 2023). Several alternative methods to adjust for the effects of timing, for application in LCA, have been proposed (Brandão et al. 2013; Brandão et al. 2019; Brandão, Kirschbaum, and Cowie 2024; Levasseur et al. 2010). Adjustment for timing was initially included in PAS2050, the UK standard for carbon footprint (BSI 2008), but subsequently removed (BSI 2011), and it remains an optional additional calculation in PAS2050, the ILCD handbook (EC-JRC-IES 2010) and the ISO standard for carbon footprint of a product (ISO 2018). Levasseur et al. (2010) developed the 'dynamic LCA' approach, which quantifies the radiative forcing resulting from an emission according to when it occurs within a defined assessment period, and assigns a reduced impact if emissions are delayed within this period. Cherubini, Peters, et al. (2011) proposed, and Guest et al. (2013) demonstrated, a method which quantifies the radiative forcing over the assessment period due to the combined effects of a pulse emission from combustion of biomass, followed by CO_2 removal due to the presumed regrowth. They devised a modified characterisation factor 'GWP_{bio}' that reflects this temporal profile of radiative forcing in comparison with a pulse emission of fossil CO_2, and varies with rotation length of the forest stand. This metric does not aim to capture the carbon stock change between a bioenergy production scenario compared to a reference scenario without the studied bioenergy production, but rather it quantifies the climate effects of actual carbon emissions and the assumed subsequent sequestration. Pingoud et al. (2012) extended the 'GWP_{bio}' concept to produce a metric that assesses the climate impacts in comparison to a reference system that includes the alternative use of the forest or agricultural land (Koponen and Soimakallio 2015).

An alternative metric to GWP, the global temperature change potential (GTP) quantifies the instantaneous effect of GHG emissions on the global temperature at a specified time (Myhre et al. 2013). GTP100 is an indicator of the potential temperature rise 100 years in the future. GTP is thus more closely related than GWP to the impact of climate change on human and natural systems but is not integrated over time. Cherubini et al. (2013) compared metrics for assessing climate impacts of forest-based bioenergy systems and demonstrated that long-rotation forest systems show greater climate-change mitigation potential when assessed by GTP than by GWP. Brandão et al. (2019) also assessed the sensitivity of results to the choice of impact assessment method and found that, where bioenergy systems involve a large change in land carbon stocks, results vary widely between metrics, to the extent that the bioenergy system may appear better or worse than the fossil fuel it replaces depending on the method applied.

Rather than applying a metric that converts emissions and removals to CO_2-equivalent, some studies have expressed climate impact as cumulative radiative forcing or absolute global warming potential (Sathre and Gustavsson 2011; Simmons et al. 2021) or absolute global temperature potential (Giuntoli et al. 2015) which enables the effect of the timing of emissions to be included implicitly. These analyses combine three analytical elements to estimate the climate implications of forest/crop management and bioenergy deployment pathways: temporally explicit life cycle system modelling to determine GHG emission profiles, atmospheric decay modelling to determine the residence of GHGs in the atmosphere and time-dependent estimates of radiative forcing due to atmospheric concentration changes of the GHGs (Sathre et al. 2013).

It is important to consider that the impact pathway from GHG emissions to climate impacts starts with emissions increasing atmospheric GHG concentrations, causing radiative forcing, leading to temperature increase and other climate impacts such as droughts and storms. There is no one metric that captures all these effects along the impact pathway; thus, it may be relevant to apply several different metrics to improve understanding of the factors that influence the outcomes and the sensitivity of results to alternative metrics. The UNEP-SETAC guide (2016) and ISO 14067 (ISO 2018) recommend applying both GWP_{100} to capture the shorter-term effects related to the rate of temperature change and GTP_{100} as a proxy for the long-term temperature rise. In a comparison of 15 metrics (Brandão, Kirschbaum, and Cowie 2024), Climate-Change Impact Potential scored highest because it reflects three different aspects of climate-change impacts (future temperature, rate of warming and cumulative warming); so it was considered the most suitable metric for comprehensively evaluating climate effects of different policy options involving bioenergy, reflecting climate impacts of timing of emissions and removals.

3.6 | Non-CO_2 GHGs and Other Climate Forcers

In addition to the impact from emissions and sequestration of CO_2, bioenergy systems can affect climate through non-CO_2 GHG emissions (e.g., CH_4 from anaerobic degradation of biomass, N_2O from soil) and non-GHG climate forcing processes. Biomass combustion, especially in traditional cookstoves, can emit black carbon (Garland et al. 2017; Shen et al. 2020). As organic aerosols emitted from trees have a cooling effect (Szopa et al. 2021), harvest of forests for bioenergy or wood products could increase warming. Effects on evapotranspiration and aerodynamic resistance also influence air temperature impacts of biomass crops (Wang et al. 2021). Biomass production can affect land surface albedo (e.g., Georgescu et al. 2011; Loarie et al. 2011) and could impact cloud formation and reflectivity, affecting global radiation balance. Forest harvest in high latitudes or altitudes with snow cover can increase albedo, reducing global warming (Bright et al. 2015). In some circumstances, this effect is substantial, counteracting warming impacts of reduction in forest carbon stock and black carbon emissions (Bright et al. 2011; Arvesen et al. 2018). It should be noted that there are substantial knowledge gaps and uncertainties related to the complex interactions between biogeochemical and physical climate forcers (Szopa et al. 2021). Current methods for calculating climate impact of bioenergy generally omit the effects of albedo and short-lived climate forcers. As impacts of short-lived climate forcers vary spatially, no single metric is universally applicable for quantifying these effects, but methods are under development (Kalliokoski et al. 2019), and a Methodology Report on Short-lived Climate Forcers is due to be published by the IPCC in 2027.

3.7 | Assessing the Climate Effects of BECCS

Assessing the climate effect of bioenergy with carbon capture and storage (BECCS) presents additional analytical complexities, particularly with respect to the choice of functional unit and handling of co-products. Emissions from CO_2 capture, transport and storage processes need to be included. BECCS facilities can take several forms, including the capture of flue gas from bio-electricity or combined heat and power production plants (e.g., Sathre et al. 2017). CO_2 can be captured from high concentration CO_2 streams released in biorefinery processes, such as fermentation in ethanol production (e.g., Dees et al. 2023; Cobo et al. 2023). Biogenic CO_2 can also be captured from existing pulp and paper mills with large point-source emissions (Onarheim et al. 2017). BECCS produces an energy product (e.g., electricity, heat, ethanol, biogas, hydrogen), sometimes other co-products (e.g., DDGS and corn oil, in the case of corn ethanol with CCS) and delivers the service of carbon dioxide removal (CDR) when the CO_2 captured is stored in geological formations or other durable storages, for example, through mineralisation.

There are instances in the literature where the entire life cycle emissions of a BECCS system have been attributed to the CDR function (e.g., Fajardy et al. 2019; Smith et al. 2024; Galik et al. 2023; Brander et al. 2021), leading to the conclusion that GHG emissions of BECCS can outweigh removals. For example, the life cycle emissions of corn ethanol with CCS across the entire supply chain (corn production, ethanol production, CCS processes) can exceed the C removal (Dees et al. 2023). However, the GHG emissions of a BECCS system should be shared among all functions of this multifunctional process, applying fundamental LCA principles and standard procedures, using allocation in ALCA, or applying credits for all displaced products in system expansion (CLCA) studies (see Section 3.2.2).

The appropriate functional unit for a BECCS process depends on the purpose of the assessment. In a study comparing energy options, emissions per unit of energy product or service is the appropriate measure. To enable comparison between CDR options, the relevant measure is emissions per unit of CDR, for example, per ton of CO_2 captured and durably stored. It may also be relevant to consider the net GHG balance per unit biomass to compare alternative uses of biomass for energy or material substitution, or to quantify the CDR per unit land area to compare BECCS based on biomass crops with CDR through reforestation (see Section 3.1). In a CLCA approach, the avoided emissions from the energy product and other co-products would be credited to the CDR function to derive the emissions per unit CDR. Alternatively, the CDR and other co-products could be credits to the BECCS energy in a CLCA with an energy function. In ALCA, the system could be subdivided, and the emissions associated specifically with the CCS processes (CO_2 capture, transport and injection) allocated to the CDR. Alternatively, allocation could be based on the carbon content of the co-products or economic value. In the example of BECCS via corn ethanol mentioned above, when the life cycle emissions are shared between the co-products of the process (ethanol, DDGS, corn oil and CDR) on the basis of C content, the emissions from CDR are one tenth of the C removal (calculated from Dees et al. 2023).

Given that BECCS is only beginning to be deployed commercially but is anticipated to play an important role in achieving climate stabilisation (IPCC 2022), prospective LCA is pertinent. BECCS could profoundly influence the climate mitigation effect of harvesting forests for bioenergy and materials by avoiding the immediate or end-of-life release of harvested biomass carbon to the atmosphere (while biomass re-grows) (Forster et al. 2021). However, due to the large energy demand of CCS, net energy displacement could be reduced (unless displaced fossil energy is also assumed to be fitted with CCS (Styles et al. 2022)). Careful identification of appropriate (displaced) energy sources is thus particularly important and could be informed by IAM-LCA coupling or by energy system modelling.

4 | Discussion and Recommendations

Quantifying the climate effects of bioenergy is a complex endeavour, and care needs to be applied when selecting the methods and interpreting the results. Bioenergy systems differ in biomass source (crop or forest systems, yield, co-products, biomass properties), supply chain processes (transport method and distance, pre-processing) and conversion process (technology, scale), so results are context-specific. Relevant, up-to-date, and unbiased assumptions for technical performance must be applied. Methodological choices influence the results and conclusions dramatically (e.g., Brandão 2022; Piccardo and Gustavsson 2021). These choices should be made carefully, according to the goal and scope of the study, and clearly stated and justified. Importantly, the interpretation of the results should be aligned with these choices.

Key decisions relate to

- Choice of spatial and temporal boundaries; sectors included (forestry/agriculture, energy, building, animal feed); reference scenario (energy system and land use);
- Climate forcing factors considered; metric used to quantify climate effects (GWP, GTP) and application of impact assessment methods that may explicitly consider timing of emissions and removals;
- Modelling approach (attributional LCA or consequential LCA applied at product scale; sectoral modelling, for example, energy system based on national borders; integrated assessment modelling at global scale);
- Assumptions about future trajectories of energy technology, energy demand, land use, competition for biomass, bearing in mind population patterns, development pathways, effectiveness of climate change policies, that determine background anthropogenic GHG emissions.

Climate effects of bioenergy are often assessed using LCA focused at the product level. For LCA studies, it is critical to capture all direct emissions in the supply chain and to assess the net benefit with respect to a plausible counterfactual, including reference land and energy systems. Indirect and non-GHG impacts should ideally be included. For product labelling or to assess compliance with scheme thresholds for emissions savings, indirect effects are often considered ‘out of scope’ due to being beyond the control of the individual economic operator; their omission has deficiencies but might be adequate if the scheme eligibility rules have been developed from studies that take indirect effects into consideration.

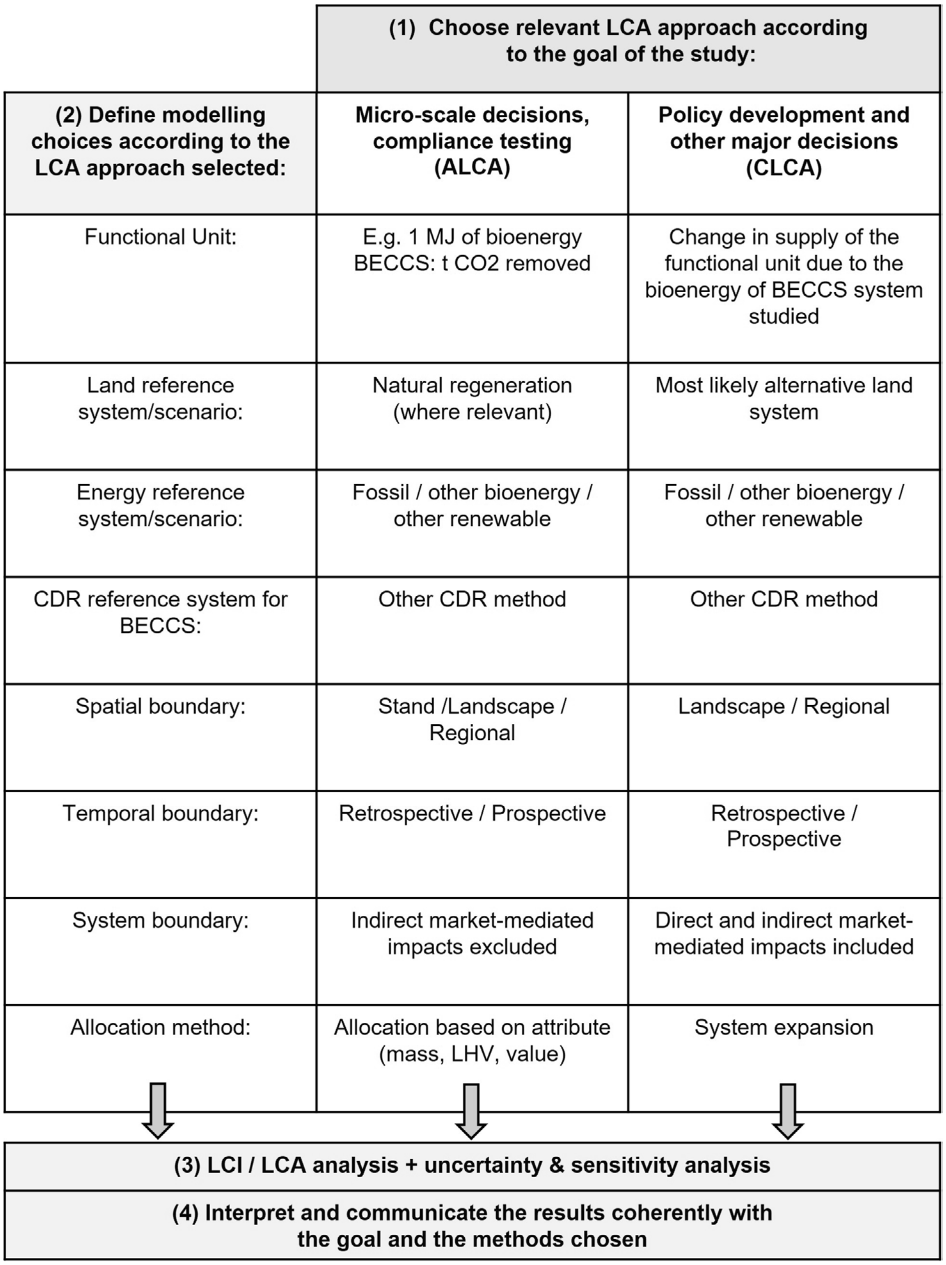
For policy-makers, the critical issue is whether the expansion of bioenergy will facilitate or hinder capacity to meet goals to stabilise the global climate, preventing warming in excess of 2° (or 1.5°). The answer will depend on how bioenergy incentives affect carbon stocks in vegetation and soil directly and indirectly, how they influence fossil fuel consumption and emissions and the transition of the energy system, and whether they leverage CDR via BECCS. The impact on vegetation and soil carbon is location-specific, influenced by environmental and socio-economic factors (e.g., bioenergy crop, climate, land ownership) that determine biophysical and land management responses. The impact on fossil fuel emissions will depend on how bioenergy availability impacts the use of fossil fuels. Importantly, for long-term energy system development and climate stabilisation, bioenergy incentives may reduce investment in new fossil-fuel technology and infrastructure, especially as bioenergy, being a storable and dispatchable energy source, can be used to stabilise electricity grids and to store energy in several forms, enabling greater expansion of intermittent renewables (e.g., solar and wind power) (Cowie et al. 2021). The role of bioenergy in supporting energy system transition is likely to shift over time, towards bioenergy for difficult-to-abate sectors such as long-distance aviation and marine transportation, and bio-based products that may still ultimately be used for bioenergy or BECCS. The biogenic CO_2 emissions from bioenergy could also be captured and utilised (BECCU) for products such as e-fuels or chemicals together with renewable hydrogen (Rodin et al. 2020; Kärki et al. 2018).

Therefore, to inform policy development, a comprehensive analysis is required, applying a combination of biophysical, climate and socio-economic models, including effects on parallel industries (e.g., wood products, animal feed, energy). Regional scale assessments that cover direct and indirect effects in all related sectors and consider multiple alternative scenarios are needed to provide an understanding of the uncertainties, the likely range of outcomes, and the key factors that influence results to support policy development. Insights from complementary methods, such as integrated assessment modelling and energy system modelling, should also be considered to inform the development of policy.

Knowledge gaps that remain to be filled, to enable more accurate assessment of the climate impacts of bioenergy and BECCS, include (i) empirical data on forest product supply and demand and land use at a resolution that enables comprehensive analyses of alternative scenarios; (ii) studies clarifying how the forestry and agriculture and energy sectors respond to socio-economic drivers (changing forest product markets, dietary preferences, renewable energy policies); (iii) studies quantifying how soil carbon dynamics and forest and crop growth respond to climate change, including the effects of increased temperature, changed rainfall, and elevated atmospheric CO_2 on growth of relevant species and (iv) methods integrating biophysical modelling of forest/agriculture systems with Earth systems-climate systems modelling, energy system modelling and integrated assessment modelling to enhance capacity for comprehensive large-scale studies. Such studies could investigate, for example, the potential for biomass crop expansion in conjunction with changes in agrifood systems to contribute to national and global net zero GHG targets, while ensuring food security.

Drawing together the elements described in preceding sections, we present below the approach recommended to obtain robust and comparable estimates of the climate effects of bioenergy systems. Users are encouraged to consider the practicability principle (Gustavsson et al. 2000), adopting an appropriate balance between rigour and practicability, commensurate with the goal of the study. Ideally, an assessment intended to inform policy development or other major decisions in government or the private sector would include all these elements.

- Clearly specify the question to be answered and the intended application of the results; choose the modelling approach consistent with these aims.
    - If the intent is to attribute a share of the climate effects of human activities to the studied bioenergy system, without looking at consequences, additionality or indirect effects, apply an attributional LCA approach (see the simplified checklist in Figure 4 that contrasts the consequential with the attributional approach.)
    - If the intent is to assess the consequences of a possible decision to introduce bioenergy or change the use of bioenergy, apply a consequential LCA approach as follows:
- Identify the appropriate land reference system for the bioenergy system being studied:apply the most likely alternative land use as a reference system/scenario. Note that the land use consequences are often not limited to the land where the biomass for the studied bioenergy systems is produced but can be far-reaching through market-mediated effects. Consider evaluating several alternative reference scenarios and convey uncertainty in projections and sensitivity of the results to the assumptions.



	(1) Choose relevant LCA approach according to the goal of the study:	
(2) Define modelling choices according to the LCA approach selected:	**Micro-scale decisions, compliance testing (ALCA)**	**Policy development and other major decisions (CLCA)**
Functional Unit:	E.g. 1 MJ of bioenergy BECCS: t CO2 removed	Change in supply of the functional unit due to the bioenergy of BECCS system studied
Land reference system/scenario:	Natural regeneration (where relevant)	Most likely alternative land system
Energy reference system/scenario:	Fossil / other bioenergy / other renewable	Fossil / other bioenergy / other renewable
CDR reference system for BECCS:	Other CDR method	Other CDR method
Spatial boundary:	Stand /Landscape / Regional	Landscape / Regional
Temporal boundary:	Retrospective / Prospective	Retrospective / Prospective
System boundary:	Indirect market-mediated impacts excluded	Direct and indirect market-mediated impacts included
Allocation method:	Allocation based on attribute (mass, LHV, value)	System expansion

(3) LCI / LCA analysis + uncertainty & sensitivity analysis

(4) Interpret and communicate the results coherently with the goal and the methods chosen

FIGURE 4 | Checklist for analysing the climate effects of bioenergy systems using methods consistent with the goal of the study.

- Identify the appropriate energy reference system for the bioenergy system being studied:apply the alternative energy system that most likely reacts to the change caused. Several alternatives could be applicable. Note that energy use may also change due to the change caused by a decision being studied.
- Choose spatial system boundaries coherently with the goal and scope of the study. Regarding land, this may vary from a forest stand/paddock or landscape to national, regional or global level, according to the scale at which the results will be applied, and the purpose; broader boundaries can capture the impacts of forest management and integrated land use systems.
- When appropriate considering the goal and scope of the study, apply a method that recognises the impact of the timing of emissions and sequestration such as the Climate-Change Impact Potential method (Brandão, Kirschbaum, and Cowie 2024) or Cumulative Radiative Forcing (Sathre et al. 2013), or use both GWP_{100} and GTP_{100} to capture longer- and shorter-term effects (Section 3.4.1).
- Choose a retrospective or prospective approach according to the purpose of the study (depending on whether it is past-looking or forward-oriented, respectively) (see, e.g., Albers et al. 2019)
- Quantify carbon stock change in vegetation and soil carbon pools over several forest or cropping rotations for short rotation systems, and at least 100 years for long rotation forests
- Choose the temporal boundary of the climate impact assessment according to the purpose of the study, acknowledging that the short-term and long-term climate impacts can be significantly different; the time horizon adopted can substantially influence the conclusions
- Choose the functional unit according to the purpose of the study. It may be relevant to present the results with respect to several functional units (e.g., related to the product, or to the biomass used) and in the case of BECCS, emissions per unit CDR is also relevant.
- For a multi-output system, handle co-products according to the hierarchy in Box 2, where possible, use subdivision to avoid allocation; otherwise, apply system expansion with substitution.
- recognising that bioenergy is typically only one component of a range of products generated from managed forest or agricultural systems, consider the flow-on effects of impacts on co-products.
- Consider all factors that influence land carbon stocks, including forest/crop management, as well as natural biotic and abiotic drivers (e.g., edaphic, climatic context; disturbance events);
- commence the analysis at the time that management changes in response to experienced or anticipated change in bioenergy demand.
- Include all climate forcers influenced by the system, that is, CO_2, non-CO_2 GHGs and ideally also aerosols and short-lived climate forcers (e.g., black carbon), and changes in land surface albedo.
- Include indirect effects mediated by market forces that impact land use, energy use, forest/land management and the wood products and food/feed sectors.
- recognise that a comprehensive analysis of climate impacts of bioenergy is complex and subject to significant uncertainties and sensitivities and clearly communicate these uncertainties and sensitivities in the results.
- Include the life cycle inventory data and sufficient detail of methods so that the results can be recalculated; for example, using a different allocation method or a functional unit.
- Note that the result is specific to each situation, so care is required in extrapolating and translating to other contexts.
- Provide an interpretation of results which is coherent with the goal and scope set and the assumptions made.

5 | Conclusion

To quantify the full climate effect of bioenergy and BECCS, to inform policy development and large-scale investment decisions, assessments should apply a whole systems perspective that considers the direct and indirect consequences of the expansion of bioenergy. This approach increases the complexity and uncertainty of assessment, compared with attributional life cycle assessment that focuses on the supply chain only, but it provides a sound basis for robust decision-making. Considering biomass for bioenergy as a component of the bioeconomy, studies should assess the effects of increasing biomass demand on carbon stocks in soil and vegetation, due to land use change or change in land management, and also include the indirect impacts on emissions (positive or negative) due to policy and market-driven influences on land use, use of wood products and fossil fuel use outside the bioenergy supply chain. The bioenergy system should be compared with a realistic and consistent counterfactual (reference system) that includes the reference land use and energy systems. The temporal boundary should represent forest/land carbon dynamics important for long-term climate stabilisation, by modelling over several rotations, and consider the trajectory for energy system transition, and short- and long-term emission reduction and climate stabilisation objectives.

Application of this methodology will support robust context-specific assessments of the climate effect of bioenergy and BECCS systems, and thereby ensure that policy decisions are informed by an accurate understanding of the contribution to climate change mitigation that bioenergy could make in that context. Use of consistent methods and interpretation will facilitate comparison between studies.

Author Contributions

Annette Cowie: conceptualization, methodology, project administration, writing – original draft, writing – review and editing. **Kati Koponen:** conceptualization, methodology, visualization, writing – original draft, writing – review and editing. **Anthony Benoist:** writing

– review and editing. **Göran Berndes:** writing – review and editing. **Miguel Brandão:** conceptualization, writing – original draft, writing – review and editing. **Leif Gustavsson:** writing – review and editing. **Patrick Lamers:** conceptualization, methodology, visualization, writing – original draft, writing – review and editing. **Eric Marland:** writing – review and editing. **Sebastian Rüter:** writing – review and editing. **Sampo Soimakallio:** writing – review and editing. **David Styles:** writing – review and editing.

Acknowledgements

We thank Helena Chum, Tat Smith, Roger Sathre, Michael Wang and Joaquim Seabra for their helpful comments. We acknowledge IEA Bioenergy for permission to utilise material from Cowie et al. (2013). Task 38 and its predecessor Tasks 15 and 25 'Greenhouse Gas Balances of Biomass and Bioenergy Systems' operated from 1995 to 2018. We acknowledge the solid foundation laid by members of these tasks and especially Bernhard Schlamadinger who led Tasks 15 and 25, and the contributions of the many people who participated in Task 38 as national team leaders and in Task 38 events. K.K. and S.S. acknowledge financial support for the green transition by the European Union (number 151, P5C1I2, NextGenerationEU, project REPower-CEST). G.B. acknowledges financial support from The Swedish Energy Agency (Navigating synergies and tradeoffs towards future forest-based solutions), The Swedish Agency for Economic and Regional Growth (Concrete action in the cement industry and the cement and concrete supply chain) and the European Union's Horizon Europe research and innovation program under the UPTAKE project (grant no. 101081521). Open access publishing facilitated by University of New England, as part of the Wiley - University of New England agreement via the Council of Australian University Librarians.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No datasets were generated during the current study.

References

Abt, K. L., R. C. Abt, and C. Galik. 2012. "Effect of Bioenergy Demands and Supply Response on Markets, Carbon, and Land Use." *Forest Science* 58: 523–539. https://doi.org/10.5849/forsci.11-055.

Agostini, A., J. Giuntoli, A. Boulamanti, and L. Marelli. 2013. *Carbon Accounting of Forest Bioenergy Critical Literature Review: JRC Technical Report, Report EUR 25354 EN*. Joint Research Centre, European Commission. https://doi.org/10.2788/29442.

Agostini, A., J. Giuntoli, L. Marelli, and S. Amaducci. 2019. "Flaws in the Interpretation Phase of Bioenergy LCA Fuel the Debate and Mislead Policymakers." *International Journal of Life Cycle Assessment* 25: 17–35. https://doi.org/10.1007/s11367-019-01654-2.

Ahlgren, S., and L. Di Lucia. 2014. "Indirect Land Use Changes of Biofuel Production–A Review of Modelling Efforts and Policy Developments in the European Union." *Biotechnology for Biofuels* 7: 35. https://doi.org/10.1186/1754-6834-7-35.

Albers, A., P. Collet, A. Benoist, and A. Hélias. 2019. "Back to the Future: Dynamic Full Carbon Accounting Applied to Prospective Bioenergy Scenarios." *International Journal of Life Cycle Assessment* 25: 1242–1258. https://doi.org/10.1007/s11367-019-01695-7.

Allen, M. 2019. "Why Protesters Should be Wary of '12 Years to Climate Breakdown' Rhetoric." https://theconversation.com/why-protesters-should-be-wary-of-12-years-to-climate-breakdown-rhetoric-115489.

Arasto, A., D. Chiaramonti, J. Kiviluoma, et al. 2017. "Bioenergy's Role in Balancing the Electricity Grid and Providing Storage Options—An EU Perspective." Task 41 P6: 2017:01.

Arvesen, A., F. Cherubini, G. del Alamo Serrano, et al. 2018. "Cooling Aerosols and Changes in Albedo Counteract Warming From CO_2 and Black Carbon From Forest Bioenergy in Norway." *Scientific Reports* 8, no. 1: 3299.

Asayama, S., R. Bellamy, O. Geden, W. Pearce, and M. Hulme. 2019. "Why Setting a Climate Deadline Is Dangerous." *Nature Climate Change* 9: 570–572. https://doi.org/10.1038/s41558-019-0543-4.

Avelino, A. F., P. Lamers, Y. Zhang, and H. Chum. 2021. "Creating a Harmonized Time Series of Environmentally-Extended Input-Output Tables to Assess the Evolution of the US Bioeconomy-A Retrospective Analysis of Corn Ethanol and Soybean Biodiesel." *Journal of Cleaner Production* 321: 128890.

Bais-Moleman, A. L., R. Sikkema, M. Vis, P. Reumerman, M. C. Theurl, and K. H. Erb. 2018. "Assessing Wood Use Efficiency and Greenhouse Gas Emissions of Wood Product Cascading in the European Union." *Journal of Cleaner Production* 172: 3942–3954.

Ballal, V., O. Cavalett, F. Cherubini, and M. D. B. Watanabe. 2023. "Climate Change Impacts of e-Fuels for Aviation in Europe Under Present-Day Conditions and Future Policy Scenarios." *Fuel* 338: 127316. https://doi.org/10.1016/j.fuel.2022.127316.

Beltran, A. M., B. Cox, C. Mutel, et al. 2020. "When the Background Matters: Using Scenarios From Integrated Assessment Models in Prospective Life Cycle Assessment." *Journal of Industrial Ecology* 24, no. 1: 64–79. https://doi.org/10.1111/jiec.12825.

Benoist, A., D. Dron, and A. Zoughaib. 2012. "Origins of the Debate on the Life-Cycle Greenhouse Gas Emissions and Energy Consumption of First-Generation Biofuels—A Sensitivity Analysis Approach." *Biomass and Bioenergy* 40: 133–142. https://doi.org/10.1016/J.BIOMBIOE.2012.02.011.

Berndes, G., N. Bird, and A. Cowle. 2010. *Bioenergy, Land Use Change and Climate Change Mitigation. Report for Policy Advisors and Policy Makers*. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2013/10/Bioenergy-Land-Use-Change-and-Climate-Change-Mitigation-Background-Technical-Report.pdf.

Bessou, C., A. Tailleur, C. Godard, et al. 2020. "Accounting for Soil Organic Carbon Role in Land Use Contribution to Climate Change in Agricultural LCA: Which Methods? Which Impacts?" *International Journal of Life Cycle Assessment* 25: 1217–1230. https://doi.org/10.1007/s11367-019-01713-8.

Bistline, J. E., and D. T. Young. 2022. "The Role of Natural Gas in Reaching Net-Zero Emissions in the Electric Sector." *Nature Communications* 13, no. 1: 4743.

Blanco, H., V. Codina, A. Laurent, W. Nijs, F. Maréchal, and A. Faaij. 2020. "Life Cycle Assessment Integration Into Energy System Models: An Application for Power-To-Methane in the EU." *Applied Energy* 259: 114160. https://doi.org/10.1016/j.apenergy.2019.114160.

Bontinck, P. A., T. F. Grant, M. Sevenster, S. Eady, and D. Crawford. 2020. "Improving Direct Land Use Change Calculations: An Australian Case Study." *International Journal of Life Cycle Assessment* 25, no. 6: 998–1012.

Brandão, M. 2022. "Indirect Effects Negate Global Climate Change Mitigation Potential of Substituting Gasoline With Corn Ethanol as a Transportation Fuel in the USA." *Frontiers in Climate* 4: 814052.

Brandão, M., E. Azzi, R. M. Novaes, and A. Cowie. 2021. "The Modelling Approach Determines the Carbon Footprint of Biofuels: The Role of LCA in Informing Decision Makers in Government and Industry." *Cleaner Environmental Systems* 2: 100027.

Brandão, M., P. Busch, and A. Kendall. 2024. "Life Cycle Assessment, Quo Vadis? Supporting or Deterring Greenwashing? A Survey of Practitioners." *Environmental Science: Advances* 3, no. 2: 266–273.

Brandão, M., R. Clift, A. Cowie, and S. Greenhalgh. 2014. "The Use of Life Cycle Assessment in the Support of Robust (Climate) Policy

Making: Comment on "Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation…"." *Journal of Industrial Ecology* 18, no. 3: 461–463.

Brandão, M., R. Heijungs, and A. R. Cowie. 2022. "On Quantifying Sources of Uncertainty in the Carbon Footprint of Biofuels: Crop/Feedstock, LCA Modelling Approach, Land-Use Change, and GHG Metrics." *Biofuel Research Journal* 9, no. 2: 1608–1616.

Brandão, M., M. U. Kirschbaum, and A. L. Cowie. 2024. "Evaluating Metrics for Quantifying the Climate-Change Effects of Land-Based Carbon Fluxes." *International Journal of Life Cycle Assessment* 29, no. 2: 328–343.

Brandão, M., M. U. F. Kirschbaum, A. L. Cowie, and S. V. Hjuler. 2019. "Quantifying the Climate Change Effects of Bioenergy Systems: Comparison of 15 Impact Assessment Methods." *GCB Bioenergy* 11: 727–743. https://doi.org/10.1111/gcbb.12593.

Brandão, M., A. Levasseur, M. U. F. Kirschbaum, et al. 2013. "Key Issues and Options in Accounting for Carbon Sequestration and Temporary Storage in Life Cycle Assessment and Carbon Footprinting." *International Journal of Life Cycle Assessment* 18: 230–240.

Brandão, M., B. Weidema, M. Martin, A. Cowie, L. Hamelin, and A. Zamagni. 2024. "Consequential Life Cycle Assessment: What, How, and Why?" In *Encyclopedia of Sustainable Technologies*, edited by M. A. Abraham, 277–284. Elsevier.

Brander, M., F. Ascui, V. Scott, and S. Tett. 2021. "Carbon Accounting for Negative Emissions Technologies." *Climate Policy* 21, no. 5: 699–717.

Bright, R. M., A. H. Strømman, and G. P. Peters. 2011. "Radiative Forcing Impacts of Boreal Forest Biofuels: A Scenario Study for Norway in Light of Albedo." *Environmental Science & Technology* 45: 7570–7580.

Bright, R. M., K. Zhao, R. B. Jackson, and F. Cherubini. 2015. "Quantifying Surface Albedo and Other Direct Biogeophysical Climate Forcings of Forestry Activities." *Global Change Biology* 21, no. 9: 3246–3266.

Briones-Hidrovo, A., J. R. C. Rey, A. C. Dias, L. A. Tarelho, and S. Beauchet. 2022. "Assessing a Bio-Energy System With Carbon Capture and Storage (BECCS) Through Dynamic Life Cycle Assessment and Land-Water-Energy Nexus." *Energy Conversion and Management* 268: 116014.

BSI. 2008. *PAS 2050:2008 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*. British Standards Institution.

BSI. 2011. "PAS 2050:2011–Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services." British Standards Institution. http://shop.bsigroup.com/en/forms/PASs/PAS-2050/.

Camia, A., J. Giuntoli, K. Jonsson, et al. 2020. *The Use of Woody Biomass for Energy Production in the EU, EUR 30548 EN*. Publications Office of the European Union.

Cavalett, O., M. D. B. Watanabe, M. Voldsund, S. Roussanaly, and F. Cherubini. 2024. "Paving the Way for Sustainable Decarbonization of the European Cement Industry." *Nature Sustainability* 7: 568–580. https://doi.org/10.1038/s41893-024-01320-y.

Cherubini, F., N. D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S. Woess-Gallasch. 2009. "Energy-And Greenhouse Gas-Based LCA of Biofuel and Bioenergy Systems: Key Issues, Ranges and Recommendations." *Resources, Conservation and Recycling* 53, no. 8: 434–447.

Cherubini, F., R. M. Bright, and A. H. Strømman. 2013. "Global Climate Impacts of Forest Bioenergy: What, When and How to Measure?" *Environmental Research Letters* 8: 029503. https://doi.org/10.1088/1748-9326/8/2/029503.

Cherubini, F., T. Gasser, R. M. Bright, P. Ciais, and A. H. Strømman. 2014. "Linearity Between Temperature Peak and Bioenergy CO_2 Emission Rates." *Nature Climate Change* 4, no. 11: 983–987.

Cherubini, F., G. P. Peters, T. Berntsen, A. H. Stromman, and E. Hertwich. 2011. "CO_2 Emissions From Biomass Combustion for Bioenergy: Atmospheric Decay and Contribution to Global Warming." *Global Change Biology. Bioenergy* 3: 413–426. https://doi.org/10.1111/j.1757-1707.2011.01102.x.

Cherubini, F., A. H. Strømman, S. Ulgiati, et al. 2011. "Influence of Allocation Methods on the Environmental Performance of Biorefinery Products—A Case Study." *Resources, Conservation and Recycling* 55, no. 11: 1070–1077.

Cintas, O., G. Berndes, A. L. Cowie, G. Egnell, H. Holmström, and G. I. Ågren. 2016. "The Climate Effect of Increased Forest Bioenergy Use in Sweden: Evaluation at Different Spatial and Temporal Scales." *Wiley Interdisciplinary Reviews: Energy and Environment* 5, no. 3: 351–369. https://doi.org/10.1002/wene.178.

Cintas, O., G. Berndes, A. L. Cowie, et al. 2017. "Carbon Balances of Bioenergy Systems Using Biomass From Forests Managed With Long Rotations: Bridging the Gap Between Stand and Landscape Assessments." *GCB Bioenergy* 9: 1238–1251. https://doi.org/10.1111/gcbb.12425.

Cobo, S., V. Negri, A. Valente, et al. 2023. "Sustainable Scale-Up of Negative Emissions Technologies and Practices: Where to Focus." *Environmental Research Letters* 18, no. 2: 023001.

Costanza, J. K., R. C. Abt, A. J. McKerrow, and J. A. Collazo. 2017. "Bioenergy Production and Forest Landscape Change in the Southeastern United States." *GCB Bioenergy* 9: 924–939. https://doi.org/10.1111/gcbb.12386.

Cowie, A., G. Berndes, and T. Smith. 2013. "On the Timing of Greenhouse Gas Mitigation Benefits of Forest-Based Bioenergy. IEA Bioenergy Executive Committee Statement 4."

Cowie, A., K. Pingoud, and B. Schlamadinger. 2006. "Stock Changes or Fluxes? Resolving Terminological Confusion in the Debate on Land-Use Change and Forestry." *Climate Policy* 6: 161–179.

Cowie, A., D. Woolf, J. Gaunt, B. Miguel, R. Anaya de la Rosa, and A. Cowie. 2015. "Biochar, Carbon Accounting and Climate Change." In *Biochar for Environmental Management*, 795–826. Routledge.

Cowie, A. L., G. Berndes, N. S. Bentsen, et al. 2021. "Applying a Science-Based Systems Perspective to Dispel Misconceptions About Climate Effects of Forest Bioenergy." *GCB Bioenergy* 13: 1210–1231.

Creutzig, F., A. Popp, R. Plevin, G. Luderer, J. Minx, and O. Edenhofer. 2012. "Reconciling Top-Down and Bottom-Up Modelling on Future Bioenergy Deployment." *Nature Climate Change* 2, no. 5: 320–327.

Curran, M. A., M. Mann, and G. Norris. 2005. "The International Workshop on Electricity Data for Life Cycle Inventories." *Journal of Cleaner Production* 13: 853–862.

Daigneault, A., J. S. Baker, J. Guo, et al. 2022. "How the Future of the Global Forest Sink Depends on Timber Demand, Forest Management, and Carbon Policies." *Global Environmental Change* 76: 102582.

Daioglou, V., G. Woltjer, B. Strengers, et al. 2020. "Progress and Barriers in Understanding and Preventing Indirect Land-Use Change." *Biofuels, Bioproducts and Biorefining* 14, no. 5: 924–934. https://doi.org/10.1002/bbb.2124.

de Carvalho Macedo, I., A. M. Nassar, A. L. Cowie, J. E. Seabra, and L. Marelli. 2015. "Greenhouse Gas Emissions From Bioenergy." *Bioenergy & Sustainability: Bridging the Gaps SCOPE* 72: 582–617.

De Rosa, M., M. T. Knudsen, and J. E. Hermansen. 2016. "A Comparison of Land Use Change Models: Challenges and Future Developments." *Journal of Cleaner Production* 113: 183–193. https://doi.org/10.1016/j.jclepro.2015.11.097.

Dees, J., K. Oke, H. Goldstein, et al. 2023. "Cost and Life Cycle Emissions of Ethanol Produced With an Oxyfuel Boiler and Carbon Capture and Storage." *Environmental Science & Technology* 57, no. 13: 5391–5403.

EC-JRC-IES. 2010. *International Reference Life Cycle Data System (ILCD) Handbook*. Joint Research Centre–Institute for Environment and Sustainability.

Edwards, R., J. F. Larivé, D. Rickeard, and W. Weindorf. 2014. "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context." Well-to-tank Report. Version 4a, April 2014. Well-to-Tank Appendix 1—Version 4a. Conversion Factors and Fuel Properties JRC Technical Reports. https://ec.europa.eu/jrc/sites/jrcsh/files/wtt_.

Elshout, P. M., M. van der Velde, R. van Zelm, Z. J. Steinmann, and M. A. Huijbregts. 2019. "Comparing Greenhouse Gas Footprints and Payback Times of Crop-Based Biofuel Production Worldwide." *Biofuels* 13: 55–61.

Energimyndigheten. 2024. "Statistics. Trädbränsle-, Torv- och Avfallspriser." Figure on Forest Chips Prices in District Heating Network. https://www.energimyndigheten.se/statistik/officiell-energistatistik/prisutveckling-inom-energiomradet/tradbransle--och-torvpriser/.

Englund, O., B. Mola-Yudego, P. Börjesson, et al. 2023. "Large-Scale Deployment of Grass in Crop Rotations as a Multifunctional Climate Mitigation Strategy." *GCB Bioenergy* 15, no. 2: 166–184. https://doi.org/10.1111/gcbb.13015.

Erlandsson, J., and F. Tannoury. 2020. "Climate Footprint on Transportation and Storage of Carbon Dioxide (CO_2)." https://www.diva-portal.org/smash/get/diva2:1469642/FULLTEXT01.pdf.

European Union. 2018. "Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy From Renewable Sources (recast), Official Journal of the European Union."

Fajardy, M., A. Koeberle, N. I. A. L. L. MacDowell, and A. N. D. R. E. A. Fantuzzi. 2019. *BECCS Deployment: A Reality Check*, 28. Grantham Institute Briefing Paper.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. "Land Clearing and the Biofuel Carbon Debt." *Science* 319: 1235–1238.

Favero, A., J. Baker, B. Sohngen, and A. Daigneault. 2023. "Economic Factors Influence Net Carbon Emissions of Forest Bioenergy Expansion." *Communications Earth & Environment* 4: 41. https://doi.org/10.1038/s43247-023-00698-5.

Favero, A., A. Daigneault, and B. Sohngen. 2020. "Forests: Carbon Sequestration, Biomass Energy, or Both?" *Science Advances* 6, no. 13: eaay6792. https://doi.org/10.1126/sciadv.aay6792.

Finnveden, G., M. Z. Hauschild, T. Ekvall, et al. 2009. "Recent Developments in Life Cycle Assessment." *Journal of Environmental Management* 91: 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Forster, E. J., J. R. Healey, C. Dymond, and D. Styles. 2021. "Commercial Afforestation Can Deliver Effective Climate Change Mitigation Under Multiple Decarbonisation Pathways." *Nature Communications* 12, no. 1: 3831.

Galik, C. S., and R. C. Abt. 2016. "Sustainability Guidelines and Forest Market Response: An Assessment of European Union Pellet Demand in the Southeastern United States." *GCB Bioenergy* 8, no. 3: 658–669.

Galik, C. S., J. S. Baker, A. Bartuska, and R. C. Abt. 2023. *Accounting Considerations for Capturing the GHG Consequences of BECCS*. Energy Futures Initiative.

Garland, C., S. Delapena, R. Prasad, C. L'Orange, D. Alexander, and M. Johnson. 2017. "Black Carbon Cookstove Emissions: A Field Assessment of 19 Stove/Fuel Combinations." *Atmospheric Environment* 169: 140–149.

Gasser, T., G. P. Peters, J. S. Fuglestvedt, W. J. Collins, D. T. Shindell, and P. Ciais. 2017. "Accounting for the Climate–Carbon Feedback in Emission Metric." *Earth System Dynamics* 8, no. 2: 235–253. https://doi.org/10.5194/esd-8-235-2017.

Georgescu, M., D. B. Lobell, and C. B. Field. 2011. "Direct Climate Effects of Perennial Bioenergy Crops in the United States." *Proceedings of the National Academy of Sciences of the United States of America* 108: 4307–4312. https://doi.org/10.1073/pnas.1008779108.

Gholami, R., A. Raza, and S. Iglauer. 2021. "Leakage Risk Assessment of a CO_2 Storage Site: A Review." *Earth-Science Reviews* 223: 103849.

Ghosh, T., S. M. Chun, S. Upasani, and P. Lamers. 2024. "LiAISON (Life-Cycle Assessment Integration Into Scalable Open-Source Numerical Models) [SWR-24-01]." https://github.com/NREL/LiAISON.

Gibbs, H. K., M. Johnston, J. A. Foley, et al. 2008. "Carbon Payback Times for Crop-Based Biofuel Expansion in the Tropics: The Effects of Changing Yield and Technology." *Environmental Research Letters* 3: 34001. https://doi.org/10.1088/1748-9326/3/3/034001.

Giuntoli, J., S. Caserini, L. Marelli, D. Baxter, and A. Agostini. 2015. "Domestic Heating From Forest Logging Residues: Environmental Risks and Benefits." *Journal of Cleaner Production* 99: 206–216. https://doi.org/10.1016/j.jclepro.2015.03.025.

Goodwin, J., M. Gillenwater, D. Romano, and K. Radunsky. 2019. *Volume1 General Guidance and Reporting Chapter 1 Introduction to National GHG Inventories. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, edited by E. Calvo Buendia and T. al. IPCC.

Grassi, G., R. Pilli, J. House, S. Federici, and W. A. Kurz. 2018. "Science-Based Approach for Credible Accounting of Mitigation in Managed Forests." *Carbon Balance and Management* 13: 8.

Guest, G., F. Cherubini, and A. H. Strømman. 2013. "Global Warming Potential of Carbon Dioxide Emissions From Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life." *Journal of Industrial Ecology* 17: 20–30.

Gustavsson, L., S. Haus, C. A. Ortiz, R. Sathre, and N. L. Truong. 2015. "Climate Effects of Bioenergy From Forest Residues in Comparison to Fossil Energy." *Applied Energy* 138: 36–50. https://doi.org/10.1016/J.APENERGY.2014.10.013.

Gustavsson, L., T. Karjalainen, G. Marland, I. Savolainen, B. Schlamadinger, and M. Apps. 2000. "Project-Based Greenhouse-Gas Accounting: Guiding Principles With a Focus on Baselines and Additionality." *Energy Policy* 28, no. 13: 935–946.

Gustavsson, L., T. Nguyen, R. Sathre, and U. Y. A. Tettey. 2021. "Climate Effects of Forestry and Substitution of Concrete Buildings and Fossil Energy." *Renewable and Sustainable Energy Reviews* 136: 110435.

Gustavsson, L., K. Pingoud, and R. Sathre. 2006. "Carbon Dioxide Balance of Wood Substitution: Comparing Concrete- and Wood-Framed Buildings." *Mitigation and Adaptation Strategies for Global Change* 11: 667–691.

Gustavsson, L., R. Sathre, P. Leskinen, G. Nabuurs, and F. Kraxner. 2022. "Comment on 'Climate Mitigation Forestry—Temporal Trade-Offs'." *Environmental Research Letters* 17, no. 4: 048001.

Gvein, M. H., X. Hu, J. S. Næss, et al. 2023. "Potential of Land-Based Climate Change Mitigation Strategies on Abandoned Cropland." *Communications Earth & Environment* 4: 39. https://doi.org/10.1038/s43247-023-00696-7.

Hakkarainen, E., I. Hannula, and E. Vakkilainen. 2019. "Bioenergy RES Hybrids—Assessment of Status in Finland, Austria, Germany, and Denmark." *Biofuels, Bioproducts and Biorefining* 13: 1402–1416. https://doi.org/10.1002/bbb.2019.

Han, J., C. Canter, H. Cai, M. Wang, Z. Qin, and J. Dunn. 2018. *Carbon Dynamics for Biofuels Produced From Woody Feedstocks*. ANL/ESD-18/10, Energy Systems Division, Argonne National Laboratory.

Henttonen, H. M., P. Nöjd, and H. Mäkinen. 2017. "Environment-Induced Growth Changes in the Finnish Forests During 1971–2010–An Analysis Based on National Forest Inventory." *Forest Ecology and Management* 386: 22–36.

Hiltunen, P., T. J. Lindroos, and M. Rämä. 2025. "The Impact of Electric Boilers and Heat Storages in the Nordic Power Markets and District Heating Systems." *Cleaner Engineering and Technology* 27: 101028.

Hodges, D. G., B. Chapagain, P. Watcharaanantapong, N. C. Poudyal, K. L. Kline, and V. H. Dale. 2019. "Opportunities and Attitudes of Private Forest Landowners in Supplying Woody Biomass for Renewable Energy." *Renewable and Sustainable Energy Reviews* 113: 109205.

Höglmeier, K., B. Steubing, G. Weber-Blaschke, and K. Richter. 2015. "LCA-Based Optimization of Wood Utilization Under Special Consideration of a Cascading Use of Wood." *Journal of Environmental Management* 152: 158–170. https://doi.org/10.1016/j.jenvman.2015.01.018.

Holttinen, H., T. J. Lindroos, A. Lehtilä, T. Koljonen, J. Kiviluoma, and M. Korpås. 2025. "Estimating the CO_2 Impacts of Wind Energy in the Transition Towards Carbon-Neutral Energy Systems." *Energies* 18, no. 6: 1548.

Houghton, J., L. Meira Filho, B. Lim, K. Treanton, and I. Mamaty. 1997. "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories." v. 1: Greenhouse Gas Inventory Reporting Instructions.-v. 2: Greenhouse Gas Inventory Workbook.-v. 3: Greenhouse Gas Inventory Reference Manual.

Hudiburg, T. W., B. E. Law, C. Wirth, and S. Luyssaert. 2011. "Regional Carbon Dioxide Implications of Forest Bioenergy Production." *Nature Climate Change* 1: 419–423. https://doi.org/10.1038/nclimate1264.

Hurmekoski, E., T. Myllyviita, J. Seppälä, et al. 2020. "Impact of Structural Changes in Wood-Using Industries on Net Carbon Emissions in Finland." *Journal of Industrial Ecology* 24: 899–912. https://doi.org/10.1111/jiec.12981.

Hurmekoski, E., C. E. Smyth, T. Stern, P. J. Verkerk, and R. Asada. 2021. "Substitution Impacts of Wood Use at the Market Level: A Systematic Review." *Environmental Research Letters* 16, no. 12: 123004.

IAMC. 2020. "What Are IAMS?" https://www.iamconsortium.org/what-are-iams/.

ICAO. 2022. "ICAO Document–CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels." https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf.

IPCC. 2006. "Agriculture, Forestry and Other Land Use." In *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, vol. 4. Intergovernmental Panel on Climate Change IGES.

IPCC. 2014. "Climate Change 2014: Mitigation of Climate Change." In *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, et al. Cambridge University Press.

IPCC. 2018. "Summary for Policymakers." In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, et al., 3–24. Cambridge University Press. https://doi.org/10.1017/9781009157940.001.

IPCC. 2019. "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use." Authors: eter (Germany), Robert William Matthews (UK), Mattias Lundblad (Sweden), Atsushi Sato (Japan), Rehab Ahmed Hassan (Sudan).

IPCC. 2021. "Summary for Policymakers." In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. MassonDelmotte et al. Cambridge University Press.

IPCC. 2022. "Summary for Policymakers." In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by P. R. Shukla et al. Cambridge University Press. https://doi.org/10.1017/9781009157926.001.

ISO. 2006a. *14040:2006. Environmental Management—Life Cycle Assessment—Principles and Framework*, 20. International Organization for Standardization (ISO).

ISO. 2006b. *14044:2006. Environmental Management—Life Cycle Assessment—Requirements and Guidelines*, 46. International Organization for Standardization (ISO).

ISO. 2015. *ISO 13065:2015. Sustainability Criteria for Bioenergy*, 57. International Organization for Standardization (ISO).

ISO. 2018. *Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification*. 1st ed. International Organization for Standardization (ISO).

Jämsén, M., D. Agar, E. Alakoski, E. Tampio, and M. Wihersaari. 2015. "Measurement Methodology for Greenhouse Gas Emissions From Storage of Forest Chips-A Review." *Renewable & Sustainable Energy Reviews* 51: 1617–1623. https://doi.org/10.1016/j.rser.2015.07.064.

Jing, L., H. M. El-Houjeiri, J. C. Monfort, et al. 2020. "Carbon Intensity of Global Crude Oil Refining and Mitigation Potential." *Nature Climate Change* 10: 526–532. https://doi.org/10.1038/s41558-020-0775-3.

Kallio, A. M. I., O. Salminen, and R. Sievänen. 2013. "Sequester or Substitute-Consequences of Increased Production of Wood Based Energy on the Carbon Balance in Finland." *Journal of Forest Economics* 19: 402–415.

Kalliokoski, T., T. Aalto, J. Bäck, et al. 2019. *Carbon Sink and CarbonSink+: From Observations to Global Potential*, 1–77. University of Helsinki.

Kärki, J., T. Thomasson, K. Melin, M. Suomalainen, H. Saastamoinen, and S. Mäkikouri. 2018. "New Business Opportunities Based on Biogenic Carbon Dioxide Utilisation." 2018. 14th Greenhouse Gas Control Technologies Conference Melbourne 21–26 October (GHGT-14). https://ssrn.com/abstract=3366310. https://doi.org/10.2139/ssrn.3366310.

Khanna, M., W. Wang, T. W. Hudiburg, and E. H. DeLucia. 2017. "The Social Inefficiency of Regulating Indirect Land Use Change due to Biofuels." *Nature Communications* 8, no. 1: 15513. https://doi.org/10.1038/ncomms15513.

Koponen, K., J. Braun, S. Cobo Gutiérrez, et al. 2024. "Responsible Carbon Dioxide Removals and the EU'S 2040 Climate Target. 1 Sept 2024." *Environmental Research Letters* 19: 091006. https://doi.org/10.1088/1748-9326/ad6d83.

Koponen, K., and S. Soimakallio. 2015. "Foregone Carbon Sequestration due to Land Occupation–The Case of Agro-Bioenergy in Finland." *International Journal of Life Cycle Assessment* 20: 1544–1556. https://doi.org/10.1007/s11367-015-0956-x.

Koponen, K., S. Soimakallio, K. L. Kline, A. Cowie, and M. Brandão. 2018. "Quantifying the Climate Effects of Bioenergy–Choice of Reference System." *Renewable & Sustainable Energy Reviews* 81: 2271–2280. https://doi.org/10.1016/j.rser.2017.05.292.

Koponen, K., L. Sokka, O. Salminen, et al. 2015. "Sustainability of Forest Energy in Northern Europe." https://publications.vtt.fi/pdf/technology/2015/T237.pdf.

Koppejan, J., and S. Van Loo. 2012. *The Handbook of Biomass Combustion and Co-Firing*. Routledge.

Kunttu, J., E. Hurmekoski, T. Myllyviita, et al. 2021. "Targeting Net Climate Benefits by Wood Utilization in Finland: Participatory Backcasting Combined With Quantitative Scenario Exploration." *Futures* 134: 102833.

Kurz, W., C. Smyth, and T. Lemprière. 2016. "Climate Change Mitigation Through Forest Sector Activities: Principles, Potential and Priorities." *Unasylva* 67: 61–67.

Lamers, P., A. F. T. Avelino, Y. Zhang, et al. 2021. "Potential Socioeconomic and Environmental Effects of an Expanding U.S. Bioeconomy: An Assessment of Near-Commercial Cellulosic Biofuel Pathways." *Environmental Science & Technology 2021* 55, no. 8: 5496–5505. https://doi.org/10.1021/acs.est.0c08449.

Lamers, P., T. Ghosh, S. Upasani, R. Sacchi, and V. Daioglou. 2023. "Linking Life Cycle and Integrated Assessment Modeling to Evaluate Technologies in an Evolving System Context: A Power-To-Hydrogen Case Study for the United States." *Environmental Science & Technology* 57, no. 6: 2464–2473. https://doi.org/10.1021/acs.est.2c04246.

Lamers, P., and M. Junginger. 2013. "The "Debt" Is in the Detail: A Synthesis of Recent Temporal Forest Carbon Analyses on Woody Biomass Forenergy." *Biofuels, Bioproducts and Biorefining* 7: 373–385.

Lamers, P., R. T. Nguyen, D. S. Hartley, J. K. Hansen, and E. M. Searcy. 2018. "Biomass Market Dynamics Supporting the Large-Scale Deployment of High-Octane Fuel Production in the United States." *GCB Bioenergy* 10, no. 7: 460–472.

Langeveld, J. W. A., M. Chordia, G. A. Oladosu, et al. 2022. *Evaluating Common Narratives, Approaches, and Tools*. IEA Bioenergy. International Energy Agency.

Laveneziana, L., M. Prussi, and D. Chiaramonti. 2023. "Critical Review of Energy Planning Models for the Sustainable Development at Company Level." *Energy Strategy Reviews* 49: 101136. https://doi.org/10.1016/j.esr.2023.101136.

Lenzen, M., B. McBain, T. Trainer, S. Jütte, O. Rey-Lescure, and J. Huang. 2016. "Simulating Low-Carbon Electricity Supply for Australia." *Applied Energy* 179: 553–564. https://doi.org/10.1016/j.apenergy.2016.06.151.

Leontief, W. 1970. "Environmental Repercussions and the Economic Structure: An Input-Output Approach." *Review of Economics and Statistic* 52, no. 3: 262–271. https://doi.org/10.2307/1926294.

Leslie, A. J. 1966. "A Review of the Concept of the Normal Forest." *Australian Forestry* 30, no. 2: 139–147.

Levasseur, A., P. Lesage, M. Margni, L. Deschênes, and R. Samson. 2010. "Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments." *Environmental Science & Technology* 44: 3169–3174.

Li, M., F. Keck, M. Lenzen, and F. Ximenes. 2024. "Flexibility Options in a 100% Renewable Grid for Australia." *Materials Today Sustainability* 26: 100736.

Li, M., E. Middelhoff, F. A. Ximenes, et al. 2022. "Scenario Modelling of Biomass Usage in the Australian Electricity Grid." *Resources, Conservation and Recycling* 180: 106198.

Lindroos, T. J., E. Mäki, K. Koponen, I. Hannula, J. Kiviluoma, and J. Raitila. 2021. "Replacing Fossil Fuels With Bioenergy in District Heating–Comparison of Technology Options." *Energy* 231: 120799. https://doi.org/10.1016/j.energy.2021.120799.

Loarie, S. R., D. B. Lobell, G. P. Asner, Q. Mu, and C. B. Field. 2011. "Direct Impacts on Local Climate of Sugar-Cane Expansion in Brazil." *Nature Climate Change* 1: 105–109. https://doi.org/10.1038/nclimate1067.

Luke. 2024a. "Luke Statistics. Removals Decreased to 75 Million Cubic Metres in 2022." https://www.luke.fi/en/news/removals-decreased-to-75-million-cubic-metres-in-2022.

Luke. 2024b. "Luke Statistics. Pulpwood and Energywood Prices Reached Record-High Levels in Wood Trade in 2023." https://www.luke.fi/en/news/pulpwood-and-energywood-prices-reached-recordhigh-levels-in-wood-trade-in-2023.

Lyngfelt, A., and B. Leckner. 2015. "A 1000 MWth Boiler for Chemical-Looping Combustion of Solid Fuels–Discussion of Design and Costs." *Applied Energy* 157: 475–487. https://doi.org/10.1016/j.apenergy.2015.04.057.

Malins, C. 2019. "Understanding the Indirect Land Use Change Analysis for CORSIA." https://www.transportenvironment.org/uploads/files/2019_12_Cerulogy_ILUC-in-CORSIA.pdf.

Malins, C., R. Plevin, and R. Edwards. 2020. "How Robust Are Reductions in Modeled Estimates From GTAP-BIO of the Indirect Land Use Change Induced by Conventional Biofuels?" *Journal of Cleaner Production* 258: 120716. https://doi.org/10.1016/j.jclepro.2020.120716.

Matthews, R., L. Sokka, S. Soimakallio, et al. 2014. "Review of Literature on Biogenic Carbon and Life Cycle Assessment of Forest Bioenergy–Final Task 1 Report, DG ENER Project, 'Carbon Impacts of Biomass Consumed in the EU'." http://ec.europa.eu/energy/renewables/studies/doc/2014_05_review_of_li.

Muench, S., and E. Guenther. 2013. "A Systematic Review of Bioenergy Life Cycle Assessments." *Applied Energy* 112: 257–273. https://doi.org/10.1016/J.APENERGY.2013.06.001.

Mun, T. Y., T. Z. Tumsa, U. Lee, and W. Yang. 2016. "Performance Evaluation of Co-Firing Various Kinds of Biomass With Low Rank Coals in a 500 MWe Coal-Fired Power Plant." *Energy* 115: 954–962.

Mutel. 2017. "Brightway: An Open Source Framework for Life Cycle Assessment." *Journal of Open Source Software* 2, no. 12: 236. https://doi.org/10.21105/joss.00236.

Myhre, G., D. Shindell, F.-M. Bréon, et al. 2013. "Anthropogenic and Natural Radiative Forcing." In *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* edited by T. F. Stocker, D. Qin, G.-K. Plattner, et al. Cambridge University Press.

Myllyviita, T., S. Soimakallio, J. Judl, and J. Seppälä. 2021. "Wood Substitution Potential in Greenhouse Gas Emission Reduction–Review on Current State and Application of Displacement Factors." *Forest Ecosystems* 8, no. 1: 42.

Nabuurs, G.-J., R. Mrabet, A. Abu Hatab, et al. 2022. "Agriculture, Forestry and Other Land Uses (AFOLU)." In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by P. R. Shukla. Cambridge University Press. https://doi.org/10.1017/9781009157926.009.

Niemi, J., S. Soimakallio, E. Hurmekoski, et al. 2025. "Carbon Credits Through Wood Use: Revisiting the Maximum Potential and Sensitivity to Key Assumptions." *GCB Bioenergy* 17: e70017.

Onarheim, K., S. Santos, P. Kangas, and V. Hankalin. 2017. "Performance and Costs of CCS in the Pulp and Paper Industry Part 1: Performance of Amine-Based Post-Combustion CO_2 Capture." *International Journal of Greenhouse Gas Control* 59: 58–73. https://doi.org/10.1016/j.ijggc.2017.02.008.

Parish, E. S., V. H. Dale, K. L. Kline, and R. C. Abt. 2017. "Reference Scenarios for Evaluating Wood Pellet Production in the Southeastern United States." *WIREs Energy and Environment* 6: e259. https://doi.org/10.1002/wene.259.

Pereira, L. G., O. Cavalett, A. Bonomi, Y. Zhang, E. Warner, and H. L. Chum. 2019. "Comparison of Biofuel Life-Cycle GHG Emissions Assessment Tools: The Case Studies of Ethanol Produced From Sugarcane, Corn, and Wheat." *Renewable and Sustainable Energy Reviews* 110: 1–12.

Piccardo, C., and L. Gustavsson. 2021. "Implications of Different Modelling Choices in Primary Energy and Carbon Emission Analysis of Buildings." *Energy and Buildings* 247: 111145.

Pingoud, K., T. Ekholm, and I. Savolainen. 2012. "Global Warming Potential Factors and Warming Payback Time as Climate Indicators of Forest Biomass Use." *Mitigation and Adaptation Strategies for Global Change* 17: 369–386. https://doi.org/10.1007/s11027-011-9331-9.

Pingoud, K., T. Ekholm, R. Sievänen, S. Huuskonen, and J. Hynynen. 2018. "Trade-Offs Between Forest Carbon Stocks and Harvests in a Steady State—A Multi-Criteria Analysis." *Journal of Environmental Management* 210: 96–103. https://doi.org/10.1016/j.jenvman.2017.12.076.

Pingoud, K., T. Ekholm, S. Soimakallio, and T. Helin. 2016. "Carbon Balance Indicator for Forest Bioenergy Scenarios." *GCB Bioenergy* 8: 171–182. https://doi.org/10.1111/gcbb.12253.

Pingoud, K., J. Pohjola, and L. Valsta. 2010. "Assessing the Integrated Climatic Impacts of Forestry and Wood Products." *Silva Fennica* 44: 155–175. https://doi.org/10.14214/sf.166.

Plevin, R. J., M. A. Delucchi, and F. Creutzig. 2014. "Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers." *Journal of Industrial Ecology* 18: 73–83.

Rajagopal, D., and R. J. Plevin. 2013. "Implications of Market-Mediated Emissions and Uncertainty for Biofuel Policies." *Energy Policy* 56: 75–82.

Rodin, V., J. Lindorfer, H. Böhm, et al. 2020. "Assessing the Potential of Carbon Dioxide Valorisation in Europe With Focus on Biogenic CO$_2$." *Journal of CO2 Utilization* 41: 101219. https://doi.org/10.1016/j.jcou.2020.101219.

Rogelj, J., D. Shindell, K. Jiang, et al. 2018. "Mitigation Pathways Compatible With 1.5°C in the Context of Sustainable Development." In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, edited by V. Masson-Delmotte, 93–174. Cambridge University Press.

Roos, A., and S. Ahlgren. 2018. "Consequential Life Cycle Assessment of Bioenergy Systems—A Literature Review." *Journal of Cleaner Production* 189: 358–373. https://doi.org/10.1016/J.JCLEPRO.2018.03.233.

Rose, S., M. Wise, V. Daioglou, et al. 2022. "EMF-33 Special Issue on Bioenergy and BECCS Parameterization and Inclusion Across IAMs." https://link.springer.com/collections/iccadadiad.

Routa, J., M. Kolström, J. Ruotsalainen, and L. Sikanen. 2016. "Validation of Prediction Models for Estimating the Moisture Content of Logging Residues During Storage." *Biomass and Bioenergy* 94: 85–93. https://doi.org/10.1016/j.biombioe.2016.08.019.

RSB. 2018. "UPM Biofuels Gains the World's First RSB Low Indirect Land Use Change (ILUC) Risk Certification for Its Feedstocks." https://rsb.org/2018/04/25/upm-biofuels-gains-the-worlds-first-rsb-low-indirect-land-use-change-iluc-risk-certification-for-its-feedstocks/.

Rüter, S., R. W. Matthews, M. Lundblad, A. Sato, and R. Hassan. 2019. Harvested Wood Products Chapter 12 Volume 4 Agriculture, Forestry and Other Land Use In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, edited by E. Calvo Buendia, K. Tanabe, A. Kranjc, et al. IPCC.

Sacchi, R., T. Terlouw, K. Siala, et al. 2022. "PRospective EnvironMental Impact asSEment (Premise): A Streamlined Approach to Producing Databases for Prospective Life Cycle Assessment Using Integrated Assessment Models." *Renewable and Sustainable Energy Reviews* 160: 112311. https://doi.org/10.1016/j.rser.2022.112311.

Sathre, R., and L. Gustavsson. 2011. "Time-Dependent Climate Benefits of Using Forest Residues to Substitute Fossil Fuels." *Biomass and Bioenergy* 35, no. 7: 2506–2516.

Sathre, R., and L. Gustavsson. 2023. "Lifecycle Climate Impact and Primary Energy Use of Electric and Biofuel Cargo Trucks." *GCB Bioenergy* 15: 508–531.

Sathre, R., L. Gustavsson, and S. Haus. 2013. "Time Dynamics and Radiative Forcing of Forest Bioenergy Systems." In *Forest Bioenergy Production: Management, Carbon Sequestration and Adaptation*, edited by S. Kellomäki. Springer.

Sathre, R., L. Gustavsson, and N. L. Truong. 2017. "Climate Effects of Electricity Production Fuelled by Coal, Forest Slash and Municipal Solid Waste With and Without Carbon Capture." *Energy* 122: 711–723.

Sathre, R., and J. O'Connor. 2010. "Meta-Analysis of Greenhouse Gas Displacement Factors of Wood Product Substitution." *Environmental Science & Policy* 13: 104–114. https://doi.org/10.1016/j.envsci.2009.12.005.

Sato, A., and Y. Nojiri. 2019. "Assessing the Contribution of Harvested Wood Products Under Greenhouse Gas Estimation: Accounting Under the Paris Agreement and the Potential for Double–Counting Among the Choice of Approaches." *Carbon Balance and Management* 14: 1–19. https://doi.org/10.1186/s13021-019-0129-5.

Schlamadinger, B., M. Apps, F. Bohlin, et al. 1997. "Towards a Standard Methodology for Greenhouse Gas Balances of Bioenergy Systems in Comparison With Fossil Energy Systems." *Biomass and Bioenergy* 13, no. 6: 359–375. https://doi.org/10.1016/S0961-9534(97)10032-0.

Schleussner, C. F., G. Ganti, Q. Lejeune, et al. 2024. "Overconfidence in Climate Overshoot." *Nature* 634: 366–373. https://doi.org/10.1038/s41586-024-08020-9.

Schmidt, J. H., B. P. Weidema, and M. Brandão. 2015. "A Framework for Modelling Indirect Land Use Changes in Life Cycle Assessment." *Journal of Cleaner Production* 99: 230–238. https://doi.org/10.1016/j.jclepro.2015.03.013.

Schulze, E.-D.-D., C. Körner, B. E. Law, H. Haberl, and S. Luyssaert. 2012. "Large-Scale Bioenergy From Additional Harvest of Forest Biomass Is Neither Sustainable nor Greenhouse Gas Neutral." *GCB Bioenergy* 4: 611–616. https://doi.org/10.1111/j.1757-1707.2012.01169.x.

Searchinger, T., R. Edwards, D. Mulligan, R. Heimlich, and R. Plevin. 2015. "Do Biofuel Policies Seek to Cut Emissions by Cutting Food?" *Science* 347, no. 6229: 1420–1422.

Searchinger, T., R. Heimlich, R. A. Houghton, et al. 2008. "Use of US Croplands for Biofuels Increases Greenhouse Gases Through Emissions From Land-Use Change." *Science* 319: 1238–1240.

Shen, X., P. Wang, X. Zhang, et al. 2020. "Real-Time Measurements of Black Carbon and Other Pollutant Emissions From Residential Biofuel Stoves in Rural China." *Science of the Total Environment* 727: 138649.

Sievänen, R., O. Salminen, A. Lehtonen, et al. 2014. "Carbon Stock Changes of Forest Land in Finland Under Different Levels of Wood Use and Climate Change." *Annals of Forest Science* 71: 255–265.

Simmons, A. T., A. L. Cowie, and C. M. Waters. 2021. "Pyrolysis of Invasive Woody Vegetation for Energy and Biochar Has Climate Change Mitigation Potential." *Science of the Total Environment* 770: 145278.

Smeets, E., A. Tabeau, S. van Berkum, J. Moorad, H. van Meijl, and G. Woltjer. 2014. "The Impact of the Rebound Effect of the Use of First Generation Biofuels in the EU on Greenhouse Gas Emissions: A Critical Review." *Renewable and Sustainable Energy Reviews* 38: 393–403. https://doi.org/10.1016/J.RSER.2014.05.035.

Smith, K. A., A. R. Mosier, P. J. Crutzen, and W. Winiwarter. 2012. "The Role of N$_2$O Derived From Crop-Based Biofuels, and From Agriculture in General, in Earth's Climate." *Philosophical Transactions of the Royal Society, B: Biological Sciences* 367, no. 1593: 1169–1174.

Smith, S., O. Geden, M. Gidden, et al. (Eds) 2024. "The State of Carbon Dioxide Removal 2024- 2nd Edition." https://doi.org/10.17605/OSF.IO/F85QJ.

Soimakallio, S. 2014. "Toward a More Comprehensive Greenhouse Gas Emissions Assessment of Biofuels: The Case of Forest-Based Fischer-Tropsch Diesel Production in Finland." *Environmental Science & Technology* 48: 3031–3038.

Soimakallio, S., A. Cowie, M. Brandão, et al. 2015. "Attributional Life Cycle Assessment: Is a Land-Use Baseline Necessary?" *International*

Journal of Life Cycle Assessment 20: 1364–1375. https://doi.org/10.1007/s11367-015-0947-y.

Soimakallio, S., J. Kiviluoma, and L. Saikku. 2011. "The Complexity and Challenges of Determining GHG (Greenhouse Gas) Emissions From Grid Electricity Consumption and Conservation in LCA (Life Cycle Assessment)–A Methodological Review." *Energy* 36, no. 12: 6705–6713.

Soimakallio, S., T. Mäkinen, T. Ekholm, K. Pahkala, H. Mikkola, and T. Paappanen. 2009. "Greenhouse Gas Balances of Transportation Biofuels, Electricity and Heat Generation in Finland—Dealing With the Uncertainties." *Energy Policy* 37: 80–90. https://doi.org/10.1016/j.enpol.2008.08.003.

Soimakallio, S., V. Norros, J. Aroviita, et al. 2025. "Choosing Reference Land Use for Carbon and Biodiversity Footprints." *International Journal of Life Cycle Assessment* 30: 54–65.

Soimakallio, S., L. Saikku, L. Valsta, and K. Pingoud. 2016. "Climate Change Mitigation Challenge for Wood Utilization–The Case of Finland." *Environmental Science & Technology* 50: 5127–5134. https://doi.org/10.1021/acs.est.6b00122.

Strengers, B., R. Matthews, G. Berndes, A. Cowie, and J. Laganière. 2024. *On the Science of Carbon Debt*. PBL Netherlands Environmental Assessment Agency.

Styles, D., J. Yesufu, M. Bowman, A. P. Williams, C. Duffy, and K. Luyckx. 2022. "Climate Mitigation Efficacy of Anaerobic Digestion in a Decarbonising Economy." *Journal of Cleaner Production* 338: 130441. https://doi.org/10.1016/j.jclepro.2022.130441.

Sumfleth, B., S. Majer, and D. Thrän. 2020. "Recent Developments in Low iLUC Policies and Certification in the EU Biobased Economy." *Sustainability* 12, no. 19: 8147. https://doi.org/10.3390/su12198147.

Sydney, E. B., L. A. J. Letti, S. G. Karp, et al. 2019. "Current Analysis and Future Perspective of Reduction in Worldwide Greenhouse Gases Emissions by Using First and Second Generation Bioethanol in the Transportation Sector." *Bioresource Technology Reports* 7: 100234.

Szopa, S., V. Naik, B. P. Adhikary, et al. 2021. "Short-Lived Climate Forcers." In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, 817–922. Cambridge University Press. https://doi.org/10.1017/9781009157896.008.

Ter-Mikaelian, M. T., S. J. Colombo, and J. Chen. 2015. "The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions About Forest Carbon Accounting." *Journal of Forestry* 113: 57–68.

Thrän, et al. 2024. "Implementation of Flexible Bioenergy in Different Countries." https://task44.ieabioenergy.com/wp-content/uploads/sites/12/2024/05/IEA-Bioenergy-Task-44_Implementation-of-flexible-bioenergy-in-different-countries-.pdf.

Tonini, D., L. Hamelin, and T. F. Astrup. 2016. "Environmental Implications of the Use of Agro-Industrial Residues for Biorefineries: Application of a Deterministic Model for Indirect Land-Use Changes." *GCB Bioenergy* 8: 690–706. https://doi.org/10.1111/gcbb.12290.

UNEP/SETAC. 2011. "Life Cycle Initiative." Global Guidance Principles for Life Cycle Assessment Databases (Shonan Guidance Principles).

UNEP-SETAC. 2016. "Greenhouse Gas Emissions and Climate Change Impacts." In *Global Guidance for Life Cycle Impact Assessment Indicators*, edited by R. Frischknecht and O. Jolliet, vol. 1. United Nations Environment Programme.

UNFCCC. 2018. "FCCC/CP/2018/L.23 From 14.12.2018 (See Annex, Section III/E2 Para 56, p. 11)."

US EPA. 2018. *Emission Factors for Greenhouse Gas Inventories*. US Environmental Protection Agency. https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf.

Vauhkonen, J., and T. Packalen. 2019. "Shifting From Even-Aged Management to Less Intensive Forestry in Varying Proportions of Forest Land in Finland: Impacts on Carbon Storage, Harvest Removals, and Harvesting Costs." *European Journal of Forest Research* 138: 219–238. https://doi.org/10.1007/s10342-019-01163-9.

Walker, T., P. Cardellichio, A. Colnes, et al. 2010. "Biomass Sustainability and Carbon Policy Study–Manomet Center for Conservation Sciencies."

Wang, J., W. Li, P. Ciais, et al. 2021. "Global Cooling Induced by Biophysical Effects of Bioenergy Crop Cultivation." *Nature Communications* 12, no. 1: 7255.

Wardenaar, T., T. Van Ruijven, A. M. Beltran, et al. 2012. "Differences Between LCA for Analysis and LCA for Policy: A Case Study on the Consequences of Allocation Choices in Bio-Energy Policies." *International Journal of Life Cycle Assessment* 17: 1059–1067.

Weidema, B. P., and J. H. Schmidt. 2010. "Avoiding Allocation in Life Cycle Assessment Revisited." *Journal of Industrial Ecology* 14: 192–195. https://doi.org/10.1111/j.1530-9290.2010.00236.x.

Ximenes, F. A., B. H. George, A. Cowie, J. Williams, and G. Kelly. 2012. "Greenhouse Gas Balance of Native Forests in New South Wales Australia." *Forests* 2012, no. 3: 653–683.

Yang, Y., W. W. Ingwersen, T. R. Hawkins, M. Srocka, and D. E. Meyer. 2017. "USEEIO: A New and Transparent United States Environmentally-Extended Input-Output Model." *Journal of Cleaner Production* 158: 308–318.

Yang, Y., and S. Suh. 2015. "Marginal Yield, Technological Advances, and Emissions Timing in Corn Ethanol's Carbon Payback Time." *International Journal of Life Cycle Assessment* 20, no. 2: 226–232.

Yu, S., J. Park, M. Kim, et al. 2019. "Improving Energy Density and Grindability of Wood Pellets by Dry Torrefaction." *Energy & Fuels* 33, no. 9: 8632–8639.

Zamagni, A., J. Guinée, R. Heijungs, P. Masoni, and A. Raggi. 2012. "Lights and Shadows in Consequential LCA." *International Journal of Life Cycle Assessment* 17: 904–918.

Zhao, X., F. Taheripour, R. Malina, M. D. Staples, and W. E. Tyner. 2021. "Estimating Induced Land Use Change Emissions for Sustainable Aviation Biofuel Pathways." *Science of the Total Environment* 779: 146238. https://doi.org/10.1016/j.scitotenv.2021.146238.

Zhao, Y. J., Y. Y. Duan, Q. Liu, et al. 2021. "Life Cycle Energy-Economy-Environmental Evaluation of Coal-Based CLC Power Plant vs. IGCC, USC and Oxy-Combustion Power Plants With/Without CO_2 Capture." *Journal of Environmental Chemical Engineering* 9, no. 5: 106121. https://doi.org/10.1016/j.jece.2021.106121.